Industrial Electric Furnaces and Appliances
Volume II

INDUSTRIAL ELECTRIC FURNACES AND APPLIANCES

VOLUME II

By V. PASCHKIS, M.E., E.E., D.Sc.

Technical Director, Heat and Mass Flow Analyzer Laboratory, Department of Mechanical Engineering, Columbia University in the City of New York.

1948

PREFACE

This second volume covers a field of furnaces in which diversity in design is much more pronounced than in the field covered by the first volume. Diversity in design may be either an expression of the ingenuity of the various designers working in a field or proof that the fundamentals are not sufficiently understood and that designs are made by rule of thumb, trial and error, or sometimes by hunches and guesses. Believing these to be the causes for the great variety of designs, the author has made a radical departure from earlier texts on such furnace problems.

The basis of any furnace problem is—or should be—a heating problem: how to heat the charge to the required uniformity at lowest cost. Therefore, the considerations of uniformity that govern the required heating time are discussed first.

The volume is divided into three chapters: Resistance Furnaces and Appliances, Induction and High-Frequency Capacitance Heating, and Selection of Furnaces. The chapter on resistance furnaces and appliances is again divided into sections on indirect-heat furnaces, direct-heat furnaces, and resistance types of appliances. In the section on indirect-heat furnaces, the design of parts, as well as of entire furnaces, is divided into subdivisions for radiation, convection, and conduction furnaces. The section on direct-heat resistance furnaces is necessarily short, since there are almost no publications on this subject, and the users of these furnaces treat information about them guardedly. In the field of resistance appliances, perhaps the first attempt to analyze the basis of design and application is made in this text. The electrical fundamentals of induction and capacitance heating are discussed quite briefly, particularly in view of the very excellent monograph on this subject by G. H. Brown and co-authors. On the other hand, the thermal aspects and the relationship between electrical and thermal problems are emphasized.

In the index the reader will find references to the various applications of furnaces and appliances. On the pages indicated the applications are listed for each general class of furnaces. The treatment of specific technologies, *e.g.*, drying, quenching, etc., is beyond the scope of this text, however. Recommendation of certain furnace types in favor of others for a given application will necessarily bring contradictions from vested interests.

An attempt is made to introduce a fairly rigid classification of furnaces and appliances, not only because it simplifies finding a desired furnace design, but also because such a system helps the reader to understand the fundamentals of such design.

v

In spite of the classification it is extremely difficult to limit the number of illustrations. Drawings, and to some extent photographs, are the language of the engineer, and help to eliminate lengthy explanations. Notwithstanding the attempt to select the drawings critically, there is still a large number of them in the text; this may be taken as proof of the large variety of designs, and accounts for the difference in length of the various sections.

The classification results also in a nomenclature that is consistent and logical. All too often, terms in furnace literature are used in an ambiguous way—describing different types of furnaces with the same words.

In writing the second volume the author tried to avoid two limits, both of which he considers undesirable for a book of this type. A text on furnaces should not be a glorified sales manual; the temptation to write the book in that manner is great, and increases with every request for illustrations. On the other hand, it should not be a text of applied physics—although, of course, any field of engineering is just that to a considerable degree. The men to whom the book is directed—the furnace engineer using furnaces, as well as the furnace designer and the power sales engineer—have no time to delve into mathematics and into theoretical considerations of heat or electrical phenomena. The judgment as to the extent to which the author has succeeded in keeping clear of these two limits, and as to his success in presenting a book in which the fundamentals of furnace design and operation are written in reasonably simple language, is left to the reader.

CONTENTS   INDUSTRIAL FURNACES   VOLUME I *

* The Table of Contents of Volume I (published 1945), is repeated here for reference purposes. The Table of Contents for Volume II will be found on page ix.

CONTENTS VOLUME II

CHAPTER FOUR

INDUCTION AND HIGH-FREQUENCY
CAPACITANCE HEATING

CHAPTER FIVE

SELECTION OF FURNACES

LIST OF SYMBOLS

a,	thermal diffusivity $= k/c\rho$	sq ft/hr
A,	area	sq ft, sq in., sq mil
b,	spacing of strips (heater ribbon)	in.
B,	thickness of electrode	in. or feet
c,	specific heat	Btu/lb
d,	diameter	in. or feet
D,	width of electrode	in.
e,	excess ratio	dimensionless
E,	voltage	v
f,	frequency	cycles/sec
g,	ratio of large side/small side; resistor ribbon	dimensionless
G_v,	ratio of voltages	dimensionless
h,	boundary conductance	Btu/sq ft, hr, F
H,	depth of immersion of electrodes	in.
i,	energy density	w/sq in.
I,	current	amp
j,	correction factor	dimensionless
k,	thermal conductivity	Btu/ft, hr, F
k_p,	correction factor for parallel circuits	dimensionless
l,	length of wire	ft
L,	inductance	henry
L,	with subscript: length	ft or in.
L_H,	1/2 thickness of material; or radius of sphere or cylinder; or thickness of wall	ft or in.
m,	relative boundary resistance	dimensionless
M_R,	number of parallel resistor circuits	dimensionless
n,	relative position in the wall	dimensionless
N_E,	number of turns or windings	dimensionless
o,	output (output in weight)	cu ft/hr (lb/hr)
p,	perimeter or part of perimeter	ft or in.
p_p,	depth of penetration	cm or in.
p'_p,	depth of penetration (alternate definition)	cm or in.
P,	performance ratio	dimensionless
P_1,	special functions for induction heating	dimensionless
P_2,		
q,	rate of heat flow	Btu/hr
r,	radius	ft or in.
R,	resistance	ohm
s,	side of resistor (smaller)	in.
S,	spacing of electrodes	in.
t,	temperature	F
T,	salt depth	in.
u,	uniformity factor	dimensionless
U,	relative depth of penetration	dimensionless
v,	velocity	ft/sec
V,	volume	cu ft or cu in.
w,	weight	lb
w_C,	correction factor for cylinders; dielectric heating	dimensionless
w_S,	correction factor for slabs; dielectric heating	dimensionless
w_s,	weight/area (page 143)	lb/sq ft
W,	power	kw or w
W_L,	reactance power	kva
W_P,	losses in primary	kw or w
X,	time value	dimensionless
y_s,	surface temperature ratio	dimensionless
y_c,	center temperature ratio	dimensionless
Y,	temperature function	dimensionless
α,	absorptivity	dimensionless
γ,	density	lb/cu ft
δ,	dielectric constant	dimensionless
ϵ,	emissivity	dimensionless
η,	efficiency	dimensionless
θ,	time	hr
λ,	wave length	meter
μ,	permeability	dimensionless
ρ,	resistivity	ohm sq mil/ft
Ξ,	temperature function	F³

xiv

Resistance Furnaces and Appliances

The terms "resistance furnaces" and "resistance appliances" are often considered to be synonymous. A practical definition would designate "furnaces" as equipment having an insulated hollow working space or chamber for the charge, whereas "appliances" neither have such a chamber for the charge nor are thoroughly insulated.

The field of resistance furnaces may be divided into "direct-heat" and "indirect-heat" furnaces (Vol. I, page 4). The indirect-heat furnaces may be grouped, according to the method by which heat is transferred from the heat source to the charge, into radiation (page 118), convection (page 153), and conduction (page 173) furnaces. The latter include salt and lead baths. For the three types uniformity and furnace size are considered together since they follow the same patterns for conduction, convection, and radiation furnaces.

Section One: Indirect-Heat Furnaces

I. FURNACE SIZE AND HEATING TIME

A. STATEMENT OF PROBLEM—UNIFORMITY

The size of an indirect-heat resistance furnace depends on the desired output of the furnace, the desired thermal uniformity of the charge, the method of heat transfer, and the size of the individual piece of the charge. The influence of the latter is obvious since the working space must be large enough to receive the largest piece of the load. The other three factors are considered together.

The volume, V (cu ft), of the working space is related to the output, o (cu ft per hr), and the necessary time of exposure, θ (hr), by:

$$V = o\theta \tag{1}$$

The time of exposure depends on the desired thermal uniformity of the charge and the method of heat transfer. The time, θ, may be considered

1

to be composed of two parts, the first part, θ_a, being the heating time required to bring the entire charge to the desired thermal uniformity, and the second part, θ_b, being a time at constant temperature. This latter time is necessary in some processes for technological (metallurgical, ceramic, etc.) reasons and is in general not influenced by the size of the piece.

The term "thermal uniformity" calls for some explanation since it has three aspects which should well be kept apart: uniformity in the workpiece; uniformity in time; and uniformity in space. The first implies that the thermal history of the workpiece should be "uniform." This is the most important condition and is treated in detail below.

Uniformity in time refers to temperature control and is defined as that condition whereby the furnace temperature at any given point is constant over a given period of time. This aspect of uniformity is treated in the section on temperature control (pages 51–63). It is often, indeed too often, erroneously quoted to prove the superiority of electric heating.[1]

Uniformity in space refers to the uniformity of temperature in the furnace under given loading conditions (*e. g.*, an empty furnace chamber or one with a given load in it). It is relatively simple to determine and is in many instances a very desirable feature and a prerequisite for obtaining uniformity in the workpiece.

Thermal uniformity in the workpiece is always relative. In surface hardening, for example, complete uniformity is not required; the surface should be at a temperature substantially higher than the center. It is relative also from the viewpoint that, as explained below, complete uniformity can never be obtained. Full thermal uniformity requires the meeting of three conditions: equal temperatures in the piece at the end of the heating period; equal rates of temperature rise at all parts of the piece and at all times; and equal times for all parts to remain at a given temperature.

It is worth remembering that for many products uniform cooling is as important as uniform heating, or more so. The following sections (pages 3–31) deal with uniform *heating* because the function of a furnace is heating. Most of the following section, however, can be applied to the often-overlooked problem of uniformity of cooling.

The three conditions can never be completely met, except in a combination of direct heating (high-frequency capacitance heating and direct resistance heating) and indirect heating. Transfer of heat from a heat source is possible only under the influence of temperature differences. To approach these three conditions as nearly as possible it would be necessary to heat the pieces at an extremely slow rate; the slower this

[1] J. A. Doyle in *Temperature, Its Measurement and Control in Science and Industry,* Reinhold, New York, 1941, p. 984. See also Vol. I, p. 16.

rate of heating the more would these ideal conditions be approached—but also the output will be correspondingly smaller.

Commercial furnace operation requires as large an output as possible; large output necessitates large temperature differences and therefore contradicts the requirement of good uniformity in the workpiece. The art of furnace design and operation, then, consists in finding the most practical and economic compromise between the requirement of output (necessitating high temperature differences) and that of uniformity (necessitating small differences).

Before discussing this aspect it should be briefly explained that if heat is generated uniformly in the charge (as may be the case in high-frequency capacitance heating and direct-heat resistance heating), the three requirements of thermal uniformity can be approached. The main obstacle to reaching thermal uniformity is the heat lost to the surroundings, but these heat losses may be offset by auxiliary indirect heating to such an extent as to cover the heat loss in each instance.

The relationship between the desired thermal uniformity and the heating time can be understood from Figure 1. The figure refers to a 4-in. steel sphere heated uniformly from all sides by exposing it to a constant furnace temperature of 2080 F; thermal conductivity, 18 Btu per ft, hr, F; specific heat, 0.15 Btu per lb, F; density, 460 lb per cu ft; boundary conductance, h, 60 Btu per sq ft, hr, F.

One curve (t_s) represents the surface temperature, a second (t_c) the center temperature, both plotted against time. A third curve (Δt) shows the difference between surface and center temperature. The final temperatures at the surface and center are not very different; they cannot be exactly the same, but the rates of temperature change, expressed in degrees per unit of time, are very different. Moreover, it can be seen that 25.6 minutes are needed to reach a uniformity of 2.4 F (1993.0 F − 1990.6 F) whereas only 19.8 minutes are needed if the temperature difference between center and surface may reach 6.6 F (1980.6 F − 1974.0 F).

In the following two sections the relationship between heating time and rate of heating are explained, the discussion referring only to a single homogeneous workpiece. Similar relationships hold for necessary heating time and length of time during which any part of the piece is exposed to a given temperature. The latter function has as yet not been reduced to a form usable for the furnace engineer.

B. Heating Time and Temperature Uniformity for Simple Bodies (Constant Furnace Temperatures)

For certain simple bodies the necessary minimum heating time can be calculated from the desired degree of temperature uniformity. For

this heating time the resulting rates of temperature rise can be found from Section C.   If the rates are too high, slower heating is necessary which results in a smaller temperature difference at the end of the heating period.   The calculations also yield the furnace temperature.
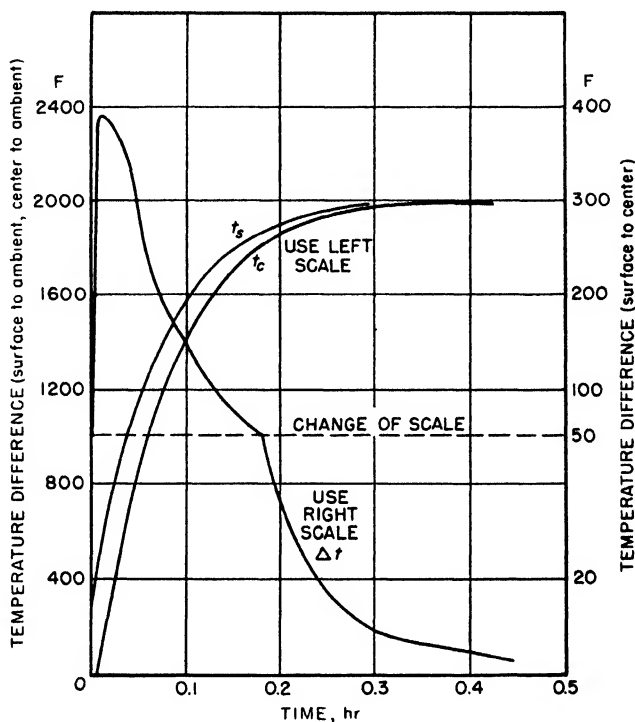
FIG. 1.   Temperature rise of steel ball.

It can be proved that a piece of given shape, size, and material can be heated to within a specified degree of temperature uniformity only in one specific value of time and at only one value of furnace temperature, provided the latter is constant during the entire heating process.

Change of heating time and/or furnace temperature results in a different degree of uniformity.   Hence, forcing the furnace, by increasing the furnace temperature and thus shortening the heating time, invariably results in a lessened temperature uniformity.

This statement, approximately correct under all circumstances, is accurate if the thermal properties of the charge do not change with temperature, the furnace temperature is constant during the entire heating time and particularly if the furnace temperature does not drop at the moment of inserting the charge, and the boundary conductance is constant.
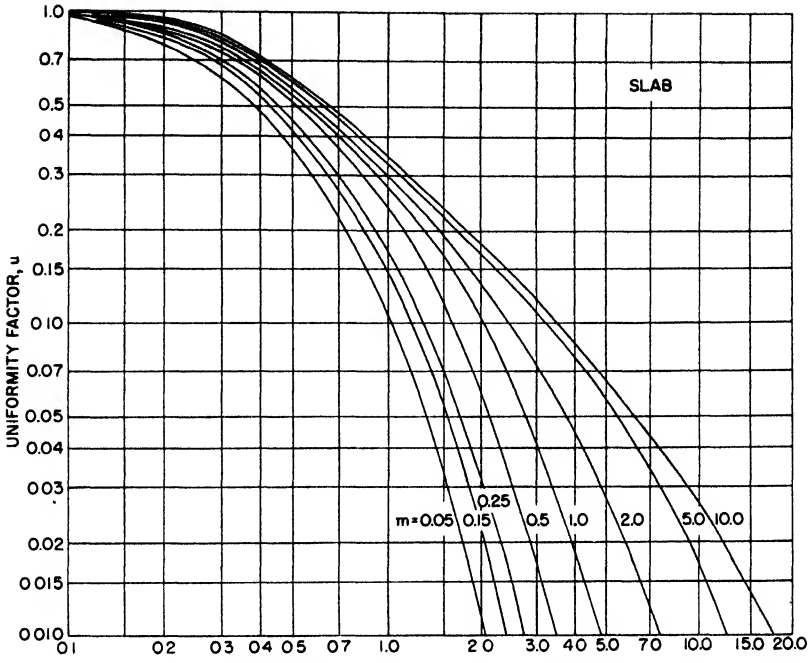
FIG. 2.   Uniformity factor for slabs.   Abscissa is $a\theta/L_H^2$.

Figures 2 to 12 are to be used for the evaluation of the heating time from the desired temperature uniformity. The following parameters have been introduced: u = uniformity factor; X = time value; m = relative boundary resistance; and y = surface temperature ratio. These parameters are defined by Equations (2) to (6):

$$u = (t_s - t_c)/t_s \quad (2) \qquad\qquad a = k/c\gamma \quad (5)$$

$$X = a\theta/L_H^2 \quad (3) \qquad\qquad y_s = t_s/t_F \qquad y_c = t_c/t_F \quad (6)$$

$$m = k/L_H \cdot h \quad (4)$$

Notations. Any consistent set of dimensions may be used, *e. g.*, those in parentheses, below:

t_F = (F) temperature of furnace (constant)⎫ measured above the initial
t_s = (F) temperature of surface⎫ of charge⎱ temperature of the charge
t_c = (F) temperature of center⎭

a = (sq ft per hr) thermal diffusivity

θ = (hr) time of heating (starting with introduction of charge into furnace)·

k = (Btu per ft, hr, F) thermal conductivity

c = (Btu per lb, F) specific heat

γ = (lb per cu ft) density

h = (Btu per sq ft, hr, F) boundary conductance

L_H = (ft) characteristic dimension (radius of cylinder or sphere, half thickness of plate)

In Figures 2 to 4 the values of u are plotted *vs.* X and m, in Figures 5 to 12 the values of y against X and m.

The values of y can be read from the Gurney-Lurie charts, as published in McAdams' *Heat Transmission.*[2] The ordinates called "Y" equal $1 - y$, following the present nomenclature. Because these charts do not permit very accurate reading, a series of graphs are presented here which were developed by Heisler,[3] using different ranges.

For small values of $X(X < 0.2)$ use Figure 5 for the slab, Figure 6 for the cylinder, and Figure 7 for the sphere. In each graph two sets of curves are shown—one for y_s, the other for my_s. For large values of $X(X > 0.2)$ and values of $m < 100$ use Figure 8 for the slab, Figure 9 for the cylinder, and Figure 10 for the sphere. These figures show as ordinates values $1 - y_c$ where y_c is t_c/t_F. The values of t_s are found by multiplying y_c with a correction factor from Figure 12. For example, for $m = 1.0$, slab, Figure 12 indicates a correction factor of 0.65. For $X = 4$, Figure 8 shows $1 - y_c = 0.06$; $y_c = 0.94$. Hence, $1 - y_s = 0.06 \times 0.65 = 0.039$ and $y_s = 0.961$.

Finally Figure 11 is used for large values of m. In this figure, $1 - y_c$ is plotted as the ordinate and values F as the abscissa, where $F = X/m$ for slabs, $2X/m$ for cylinders, and $3X/m$ for spheres. Values of $m > 100$ occur in practice only if the treated piece is thin. Then temperature differences in the piece may generally be neglected, and the heating time can be calculated directly from Figure 11. The use of the figures is carried out in steps, as illustrated in the following examples.

A steel ball of 8-in. diameter uniformly exposed on all sides to heat, is to be heated to a surface temperature of 1570 F and within a temperature uniformity of 40 F.

Determine the desired value of u. The center temperature $t_c = 1570 - 40 = 1530$ F; hence

$$u = \frac{1570 - 1530}{1570} = 0.02547$$

Determine the value of m. With an estimated furnace temperature of 1600 F and a surface temperature of 1570 F, the value Ξ for radiation can be read from Figure 9 in Volume I.

$$\Xi = 340$$

Hence (assuming an emissivity of $\epsilon = 0.92$) the boundary conductance becomes $h = 54$, and

$$m = \frac{21.6}{54 \times \frac{8}{2} \times \frac{1}{12}} = 1.2$$

[2] W. H. McAdams, *Heat Transmission.* McGraw-Hill, New York, 1942.

[3] M. P. Heisler, "Temperature Charts for Induction and Constant Temperature Heating," *Trans. Am. Soc. Mech. Engrs.*, **69**, 227 (1947).
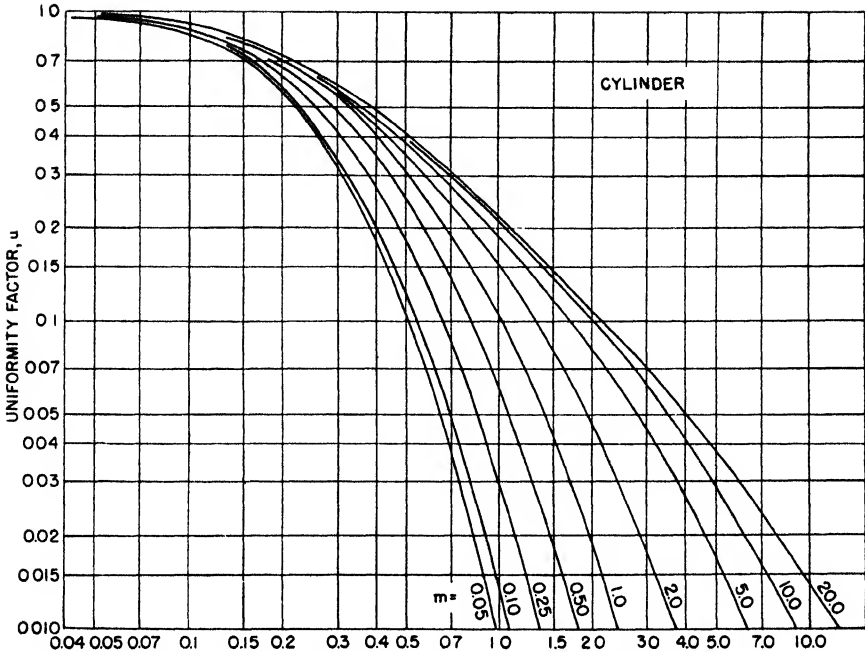
FIG. 3. Uniformity factor for cylinders. Abscissa is $a\theta/L_H^2$.

Read the value of X. For the sphere use Figure 4. Follow the arrows drawn for this example.

$$X = 1.35$$

Determine time, θ. Use Equation (3).

$$\theta = (8\tfrac{1}{2} \times \tfrac{1}{12})^2 \frac{X}{a} = 0.555 \text{ hr}$$

(For steel at an average temperature of 800 F the diffusivity can be estimated, $a = 0.27$ sq ft per hr.)

Determine y. From Figure 10 determine for $X = 1.35$ and $m = 1.2$.

$$1 - y_c = 0.075$$

From Figure 12 determine for $m = 1.2$ and for the sphere the correction factor 0.678. Hence $1 - y_s = 0.075 \times 0.678 = 0.0508$.

$$y_s = 0.949$$

Determine t_F. Use Equation 6. The surface temperature t_s is given (1570 F). Hence the furnace temperature is $t_F = (1570 - 70)/y_s = 1500/0.949 = 1581$. Adding the ambient temperature of 70 F the furnace temperature of 1651 is obtained. If the furnace temperature turns out to be very far from the estimated value (1600 F), then the procedure is repeated with new estimated values of h and m.

There also can be found from these charts the results obtained from "forcing the furnace," *i. e.*, increasing the furnace temperature without changing the ultimate surface temperature of the charge.

Example. If in the above example the furnace temperature were deliberately set at 1751 F instead of at the calculated value of 1651 F, then y_c would be only 0.892 instead of the originally found $y_s = 0.949$.

Then by reversing the entire procedure a value for $u = 0.059$ would be found. Inasmuch as t_s is unchanged, the temperature difference would be $t_v - t_c = 88.5$ F instead of the previous value of 40 F. Forcing the furnace has resulted in less uniformity of temperature.
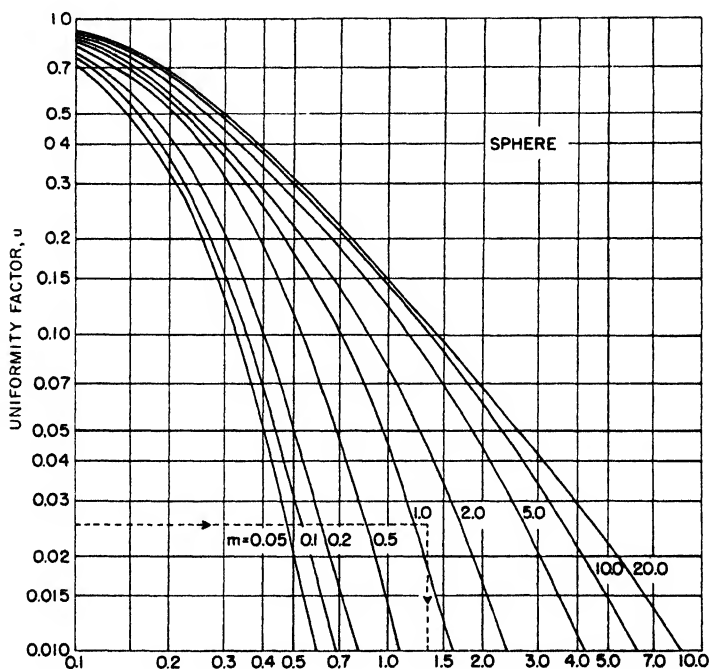
FIG. 4.   Uniformity factor for spheres.   Abscissa is $a\theta/L_H^2$.

Actually the lack of uniformity will be somewhat less accentuated than in the example where a constant value of h was assumed. With increasing furnace temperature the value of h increases automatically, hence m decreases. From the charts it follows that the temperature difference is smaller for lower m. However the change in h due to the increase of furnace temperature possible in practice is not large enough to affect appreciably the above statement.

The necessity for prolonged heating time with increased required degree of temperature uniformity is exemplified in Figure 13, which shows
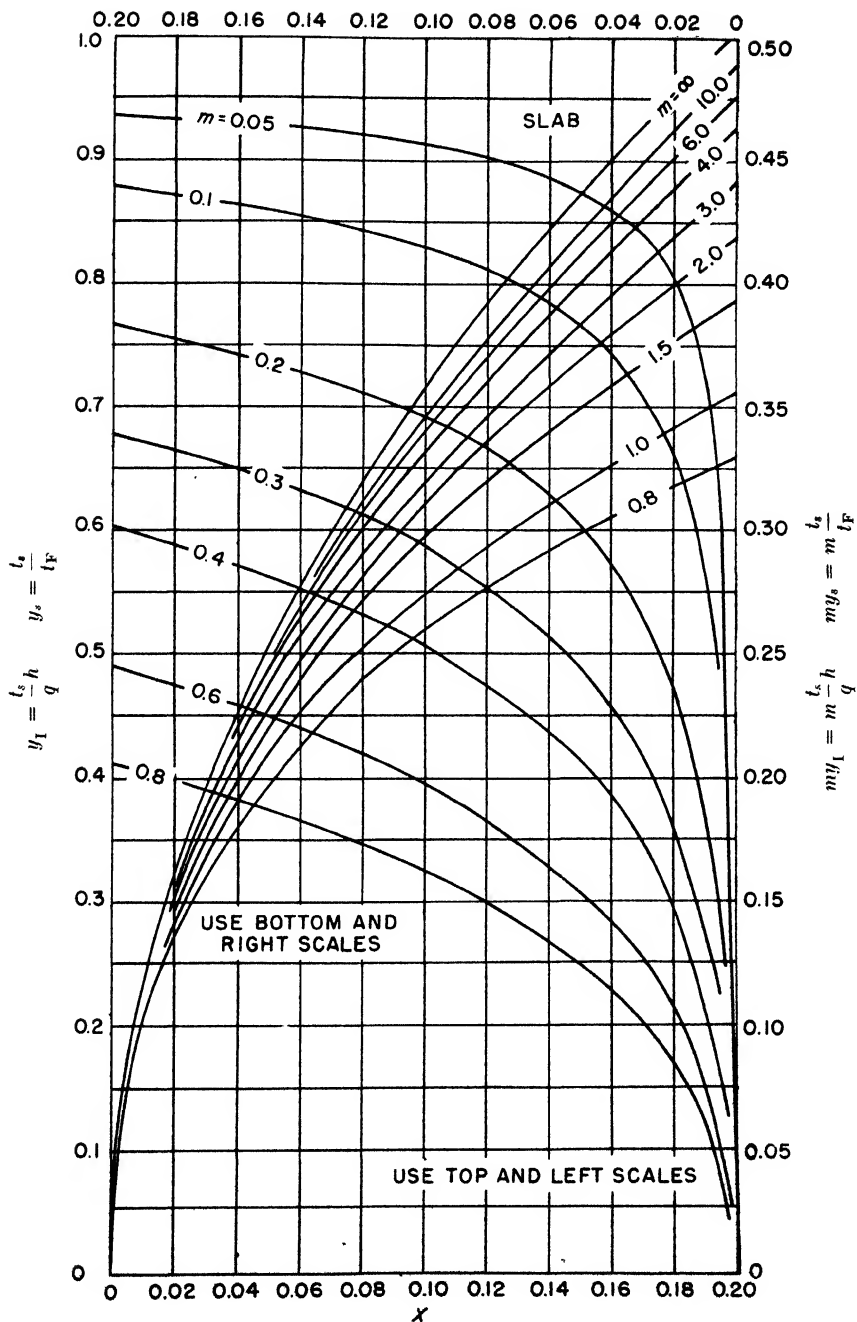
FIG. 5. Temperature function (y) for surface of slabs—small X.
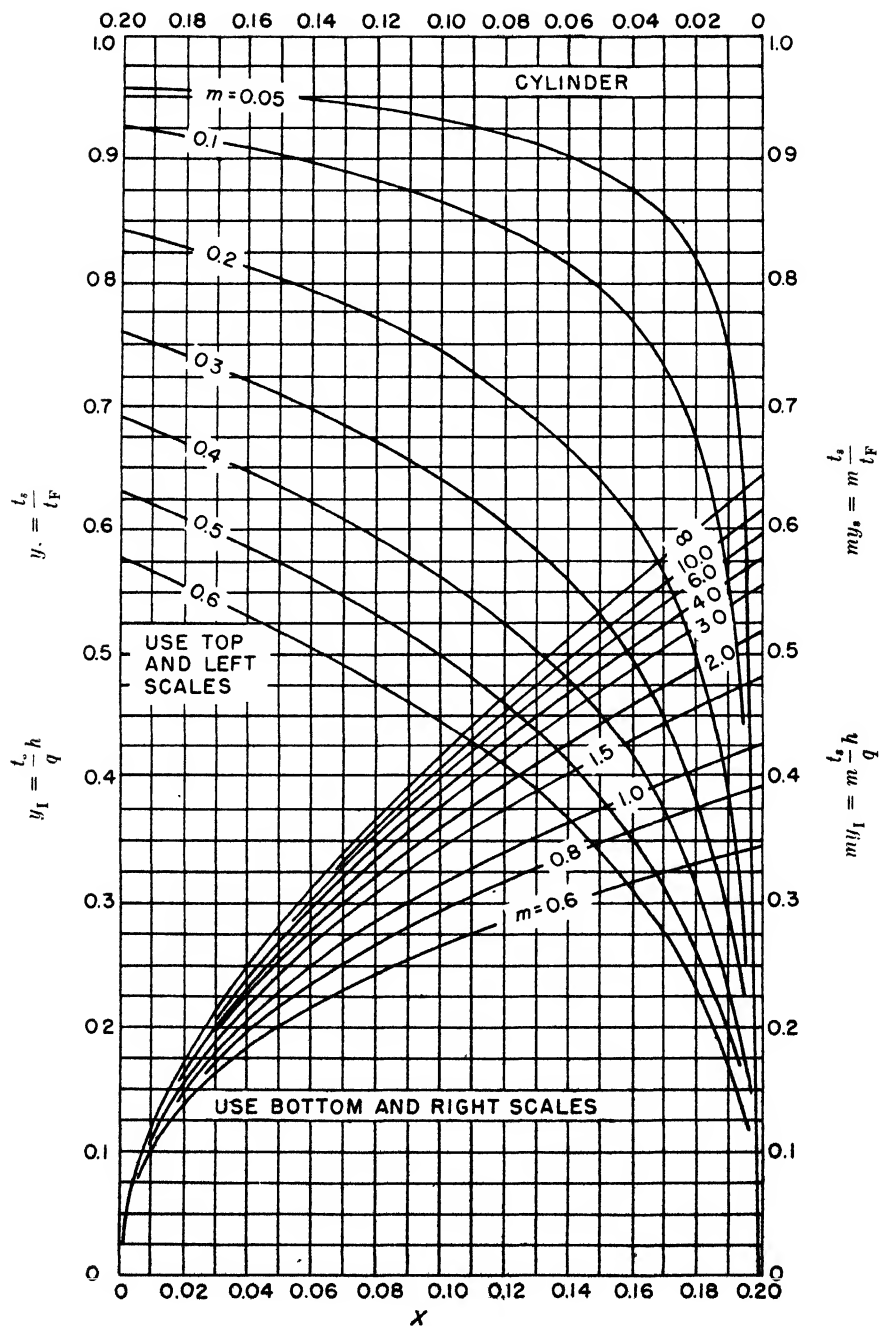
FIG. 6. Temperature function (y) for surface of cylinders—small X.
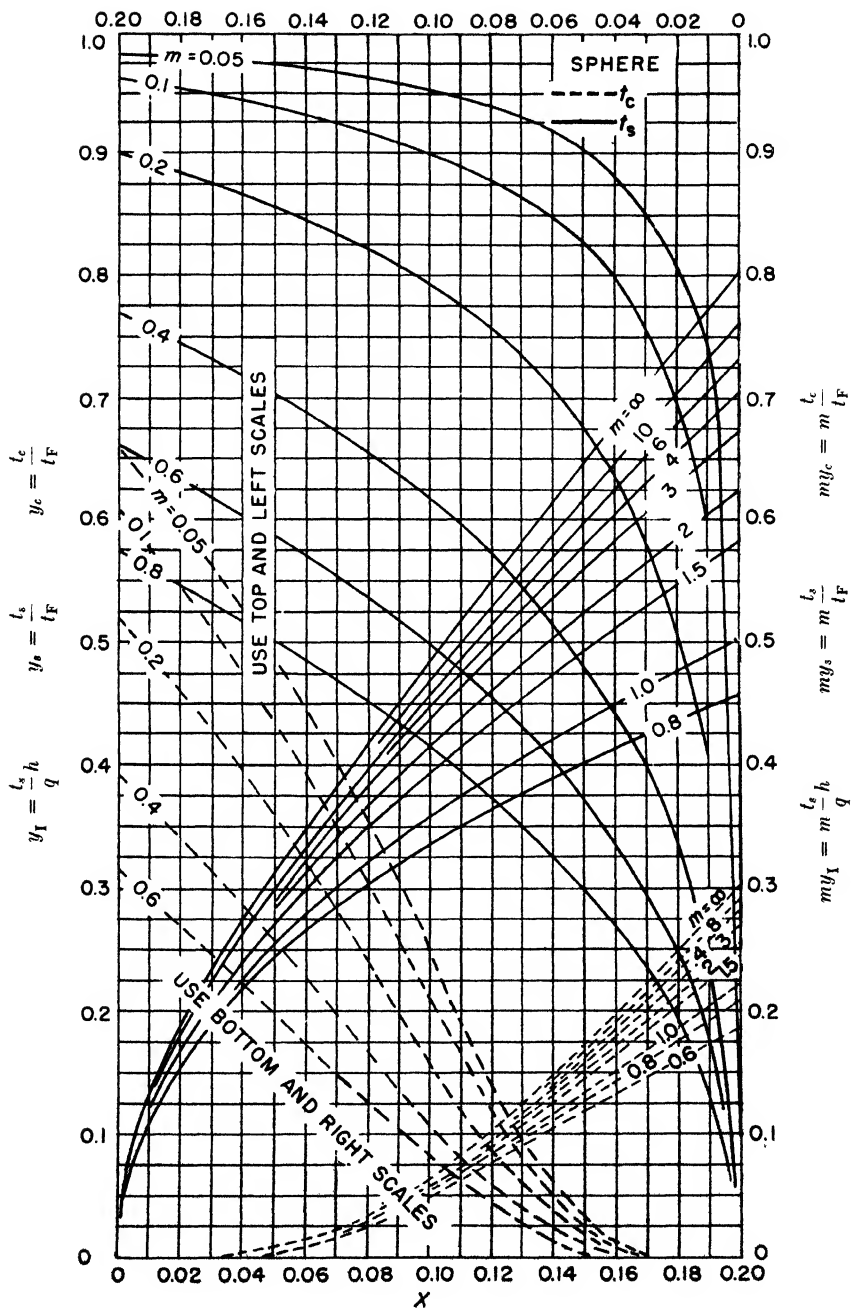
FIG. 7. Temperature function (y) for spheres—small X.
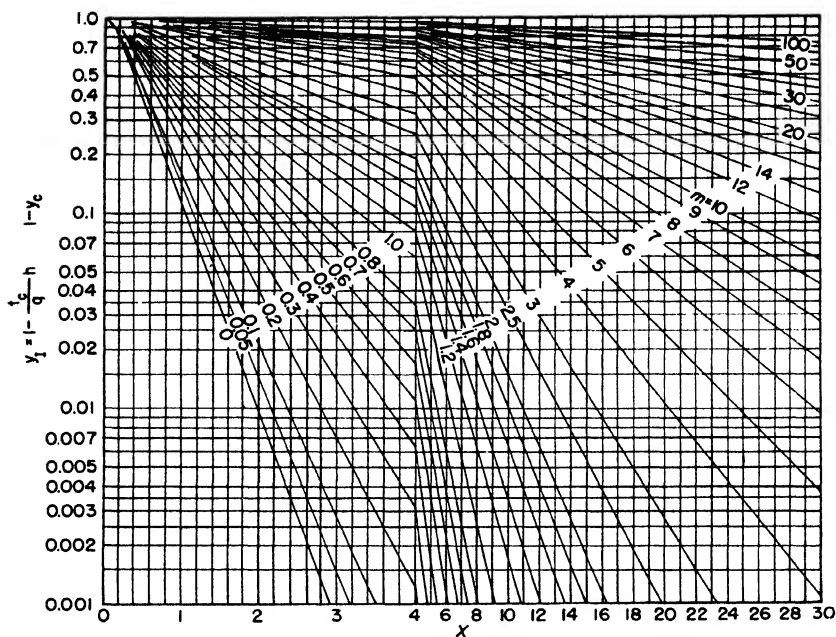
FIG. 8. Temperature function (y) for center of slabs—large X.
(a) X values 0–30   (b) X values 30–700. (Continued on p. 13.)
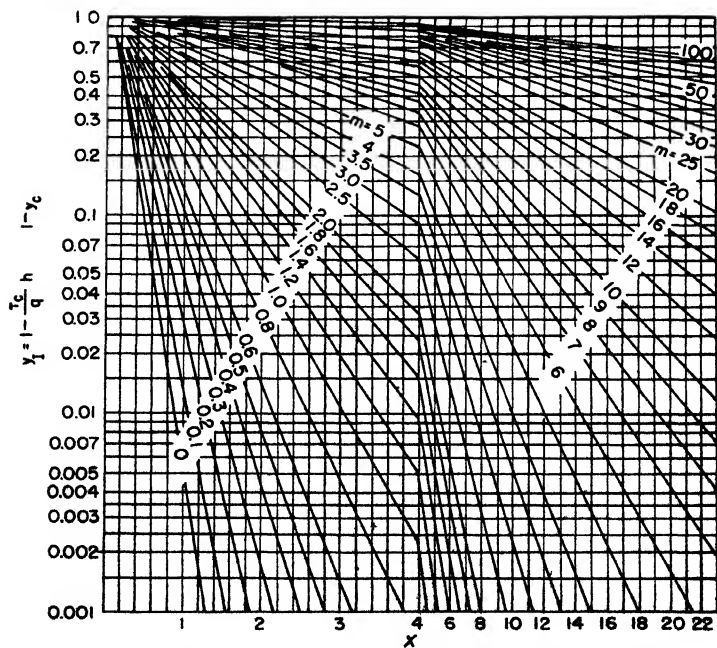
FIG. 9. Temperature function (y) for center of cylinders—large X.
(a) X values 0–23   (b) X values 23–350. (Continued on p. 13.)
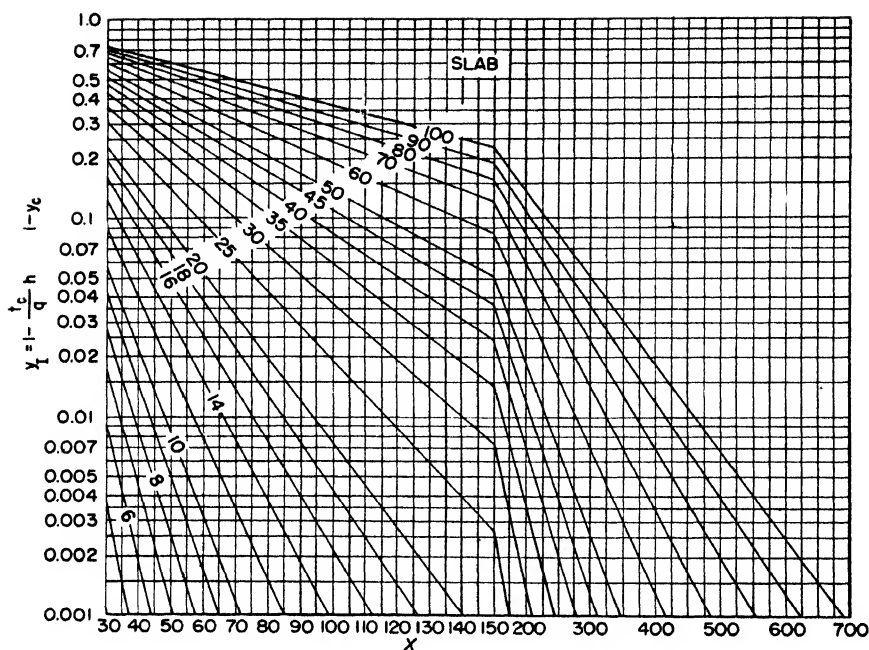
FIG. 8 (concluded).   Temperature function (y) for center of slabs   large X.
(a) X values 0–30   (b) X values 30–700.
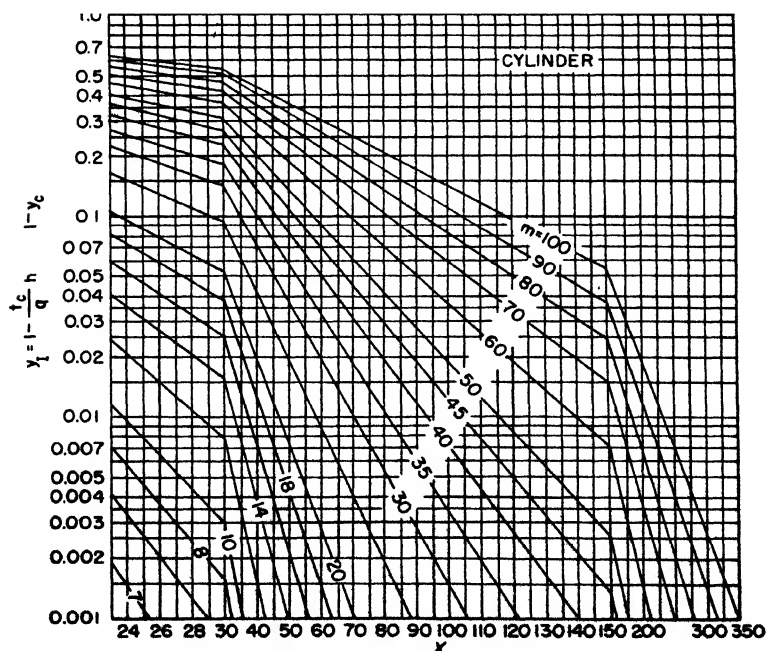
FIG. 9 (concluded).   Temperature function (y) for center of cylinders—large X.
(a) X values 0–23   (b) X values 23–350.
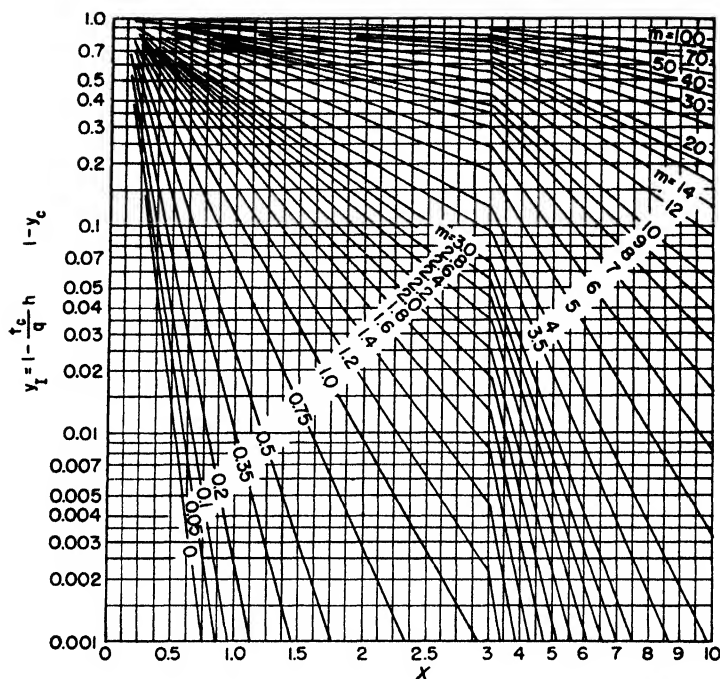
Fig. 10. Temperature function (y) for center of spheres— large X.
(a) X values 0–10   (b) X values 10–250. (Continued on p. 15.)

the necessary heating time (ordinate) plotted against the desired temperature difference between surface and center (abscissa). The curves hold for a steel cylinder of 6-in. radius having the physical properties specified in the caption.

Curve a is drawn for a value of $h = 60$ Btu per sq ft, hr, F which is a reasonable assumption for heat transfer by radiation in the range of 1800 F. Curve b is drawn for a value of $h = 80$ Btu per sq ft, hr, F; such a value may be expected for heat transfer by radiation, increased by convection through artificial air circulation. Curve c finally shows the theoretical lower limit obtained with $h = \infty$. Such a condition can never be actually reached, but is approached with heating in a lead or salt bath, if the effect of freezing of salt or lead on the surface of the piece is neglected (see page 175).

Thus it becomes obvious that a furnace specification is incomplete if it indicates merely one temperature of the charge but fails to state the desired temperature uniformity in the charge. Figure 13 shows also very clearly the influence of the desired uniformity on the necessary heating time. It must be kept in mind that (apart from the necessary holding time) the furnace volume is directly proportional to the heating time.

A different method of calculating uniformities is used by Heisler.[4]

[4] M. P. Heisler, *Trans. Am. Soc. Mech. Engrs.*, **68**, 493 (1946).
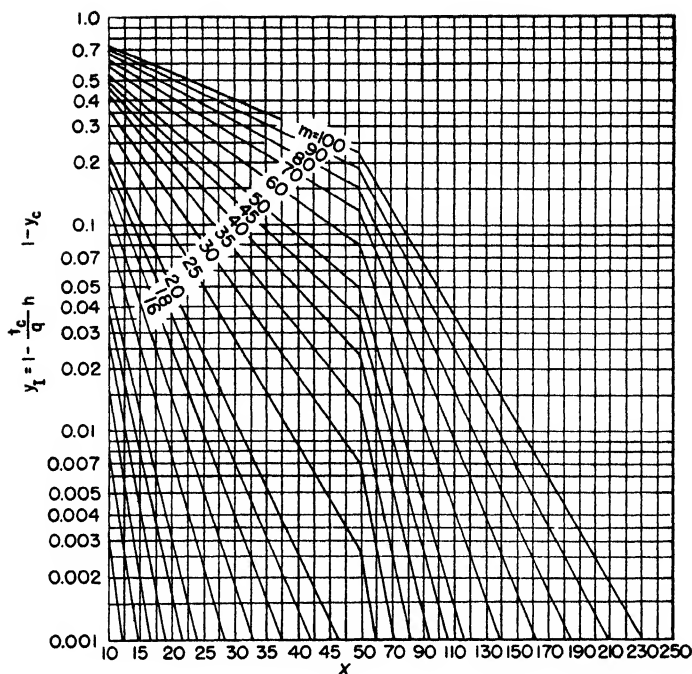
FIG. 10 (concluded). Temperature function (y) for center of spheres—large X.
(a) X values 0–10   (b) X values 10–250.

Recent investigations by Jackson and coauthors [5] show that, for heavy sections heated up together with the furnace, the time to produce uniform temperatures can be determined, if the time for raising the surface temperature for the last 100 C is known. The authors also develop a slide rule and alignment chart for such computations.

C. RATE OF HEATING

Rate of heating is defined as the ratio "degrees of temperature increase per unit time." Little has been published concerning actual or permissible rates of heating or cooling. Publications that do exist refer only to the rates at the surface and do not consider the large differences between rates at the surface and within the body.

Rates of heating can be presented in charts using dimensionless units, similar to those used for temperatures. Figure 14 may serve as example.[6] The same notations as are used for Figures 2 to 12 apply. Dimensionless times X are plotted as abscissas, and the rates are plotted

[5] R. Jackson, R. J. Sarjant, J. B. Wagstaff, N. R. Eyres, D. R. Hartree, and J. Ingham, paper 15, Alloy Steels Research Committee of the Iron and Steel Institute, 1944.
[6] V. Paschkis, *Welding J. N. Y.* (*Research Supplement*), 25, 497s (1946).
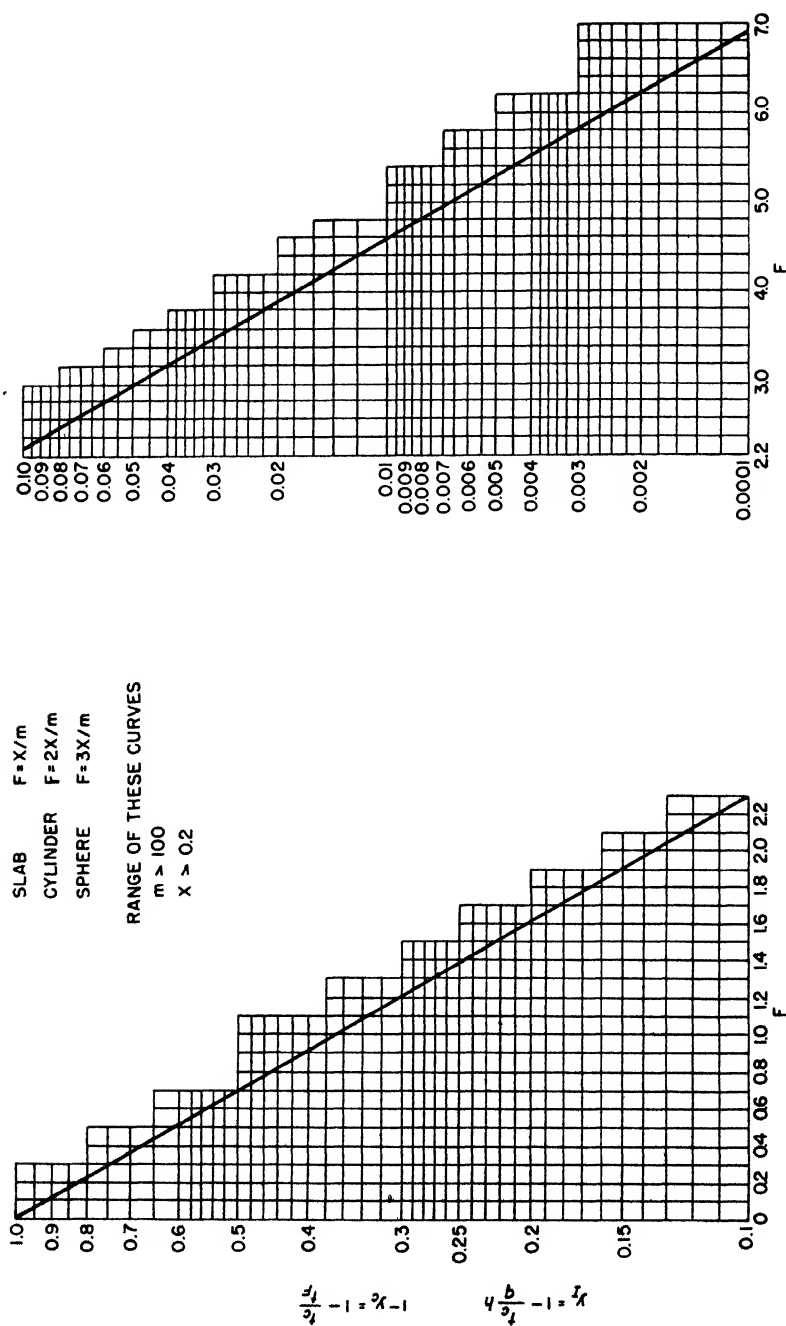
Fig. 11. Temperature function (y) for large m.
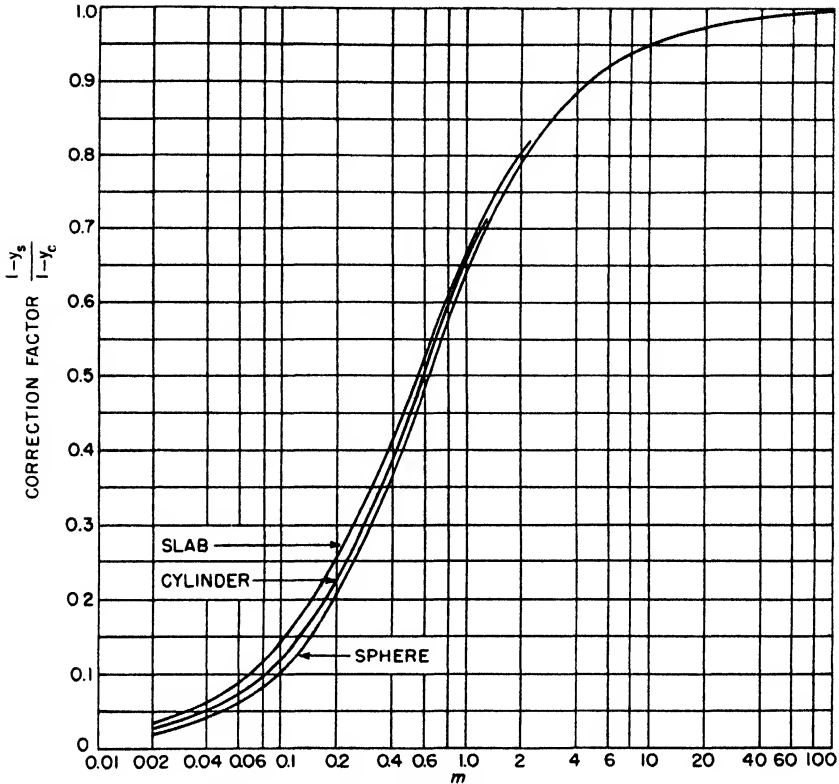
FIG. 12. Correction factor for surface temperatures.

as ordinates. The rates are expressed by dy/dX. In order to apply the curves to a specific case (example in parentheses) determine:

(1) The relative boundary resistance $m(m = 0.1)$.

(2) The dimensionless times $X(X = 0.3)$.

(3) The temperature difference (t_F) between furnace and ambient (1600).

For these values read the ordinate. (For the values given as examples in parentheses the ordinate is 1.4. Multiply the ordinate with L_H/a (e. g., $1/(0.34 \times 144)$ for a slab $2L_H = 2$-in. thick and with a diffusivity $a = 0.34$ sq ft per hr, heated from an ambient temperature of 70 F in a furnace having a constant temperature of 1670.) Then at the time XL_H^2/a (e. g., $0.3/(0.34 \times 144) = 0.00613$ hr $= 22.1$ sec) a rate of $t_F \times a/L_H^2 \times dy/dX$ prevails (e. g., $(1670 - 70) \times 0.34 \times 144 \times 1.4$ $= 109{,}070$ F per hr $= 30.5$ F per sec).

Since it is difficult to visualize the nature of curves from dimensionless units, Figure 15 is presented. A long steel cylinder, 6-in. in diameter, is

Fig. 13. Heating time *vs.* temperature difference between surface and center.

Example: Steel cylinder, 12 in. diameter

$k = 18.6$ Btu/ft, hr, F
$a = 0.27$ sq ft/hr
Surface temperature
$= 1870$ F
Ambient temperature
$= 70$ F
For a, $h = 60$ (radiation)
b, $h = 80$ (radiation + convection)
c, $h = \infty$ (conduction —salt bath)
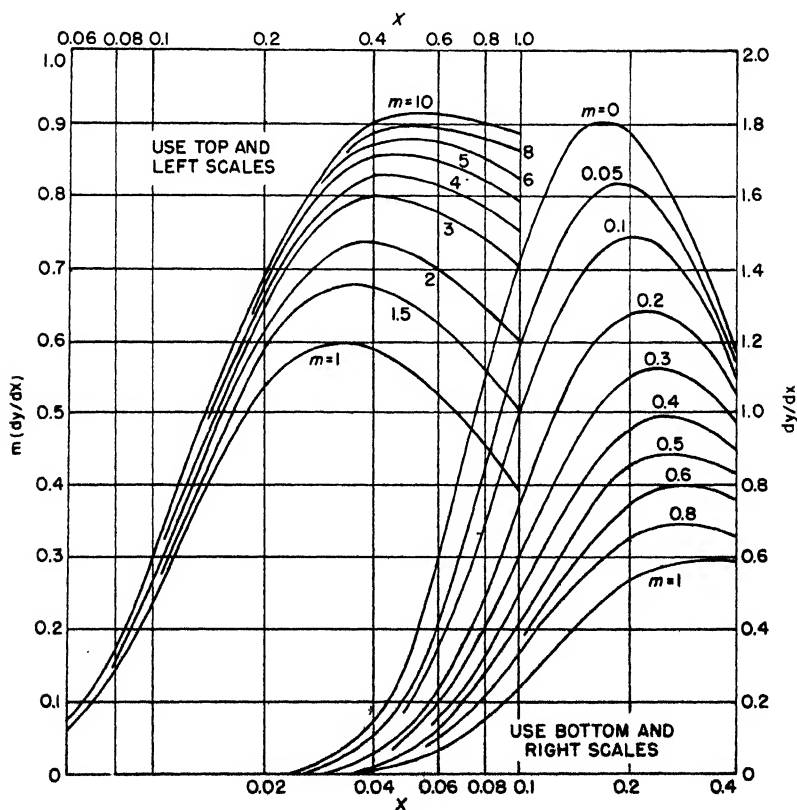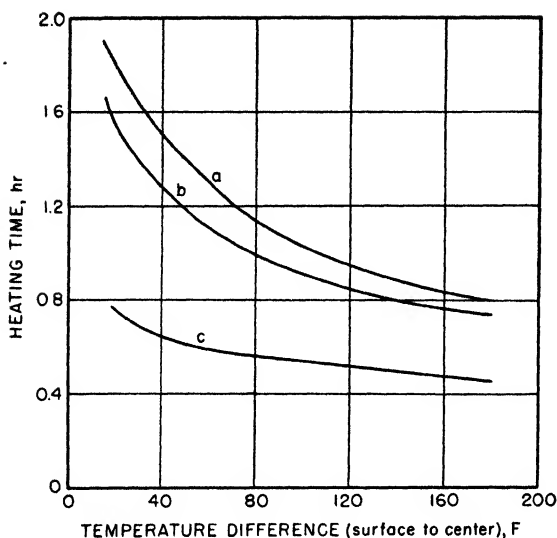
Fig. 14. Heating and cooling rates for center of slabs—general chart.

heated by exposure to a constant temperature of 1650 F. The rates at the center and at points with a distance from the center of 0.516 and 0.98 of the radius (the latter almost at the surface) are shown in Figure 15 as functions of time. The curves were calculated from charts given by Paschkis.[6]
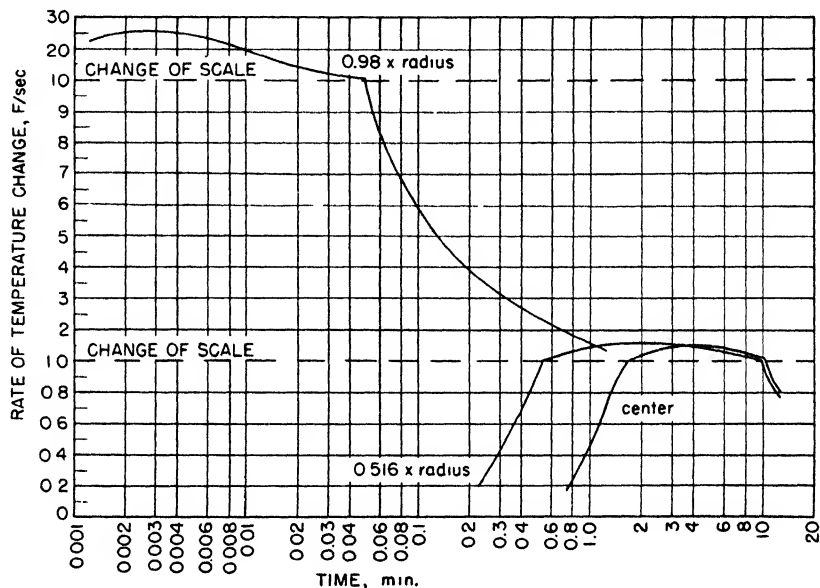
Fig. 15. Heating and cooling rates. (Cylinder 6-in. diameter, 1650 F furnace temperature.)

D. Furnace Temperature Not Constant

So far it has been assumed that the furnace temperature is constant during the entire heating of the load. However a certain acceleration of the heating without sacrifice of final temperature uniformity can be obtained by increasing the furnace temperature as much as possible at the outset. As soon as the surface of the load reaches the upper limit of the temperature range permissible for the charge, the furnace temperature is dropped to a value barely above the load temperature. The small temperature difference between the new furnace temperature and the surface temperature results in only a small heat flow toward the load, which flow is required to bring the inside of the load up to the desired final temperature.

However, this procedure results in a stronger accentuation of differences in *rates* of temperature change at the surface and the center. As a limiting case the conditions of induction heating with very high energy density can be approached, where the maximum permissible surface temperature is reached almost instantaneously and almost the entire heating time is required to bring the center to the desired temperature.

Instead of one sudden change of furnace temperature a gradual decrease would be desirable; as the heating of the charge proceeds, the furnace temperature would be steadily decreased, in order to avoid overheating of the surface.   Practical application of this method is difficult except for continuous furnaces; there the change of furnace temperature just mentioned is replaced by subsequently exposing the load to different zones of the furnace, each having a different, but practically constant temperature.
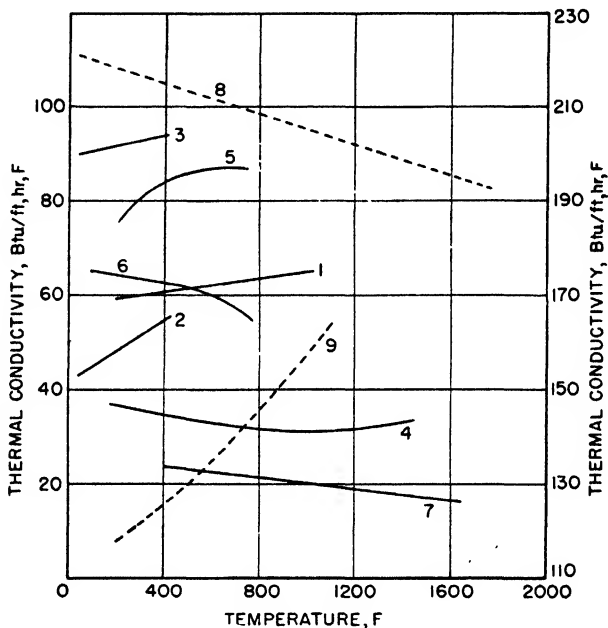
FIG. 16.   Thermal conductivities of various materials:

1, pure magnesium
2, magnesium + 6% aluminum
3, magnesium + 0.5% manganese
4, technically pure nickel   use left
5, brass, 30/70   scale
6, zinc
7, steel

8, copper   }use right
9, aluminum/   scale

Where the requirements for uniformity are low, this method can be applied by heating rapidly only until the surface temperature reaches the lower limit of the desired temperature range.   Then as the piece becomes "soaked" with heat the surface temperature will gradually increase; but under favorable conditions this increase may not exceed the difference between desired maximum and minimum temperature of the piece.

From a study of Figures 5 to 12 it becomes obvious that the most effective way of increasing heating time is not by complicated temperature control or manipulation but by simply exposing to heat individual pieces,

not piles of pieces. A remarkably high degree of uniformity can be achieved even in fairly thick pieces within relatively limited time. And it is surprising how poor the uniformity becomes if even only a very few air spaces between the pieces of the load change the pattern of straight conduction to a problem of conduction and subsequent radiation. These remarks apply of course mainly to metals; in heating poor conductors, e. g., refractory bricks or porcelain ware, the time required for uniformity is always long; in such instances heating by high-frequency capacitance results in more uniform temperature in shorter time.
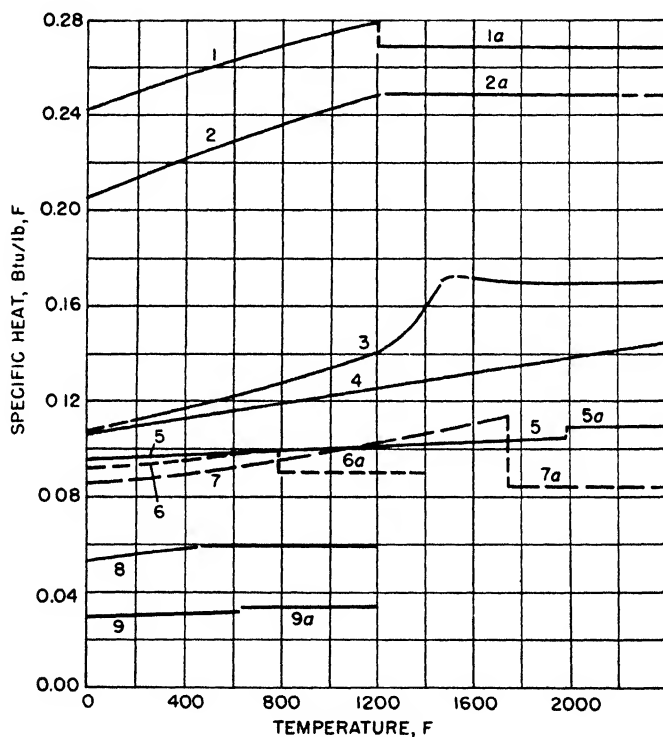
Fig. 17. Specific heat of various materials: 1, magnesium; 2, aluminum; 3, steel; 4, nickel; 5, copper; 6, zinc; 7, brass (70% Cu, 29% Zn, 1% Sn); 8, tin; 9, lead. Letter *a* indicates molten stage.

E. Selection of Properties

In order to utilize the above charts (Figures 2–12 and 14) the physical properties—thermal conductivity, specific heat, density, and boundary conductance—must be known.

Conductivity, specific heat, and boundary conductance are functions of temperature. In Figure 16 thermal conductivities are plotted as functions of temperature. In Figure 17 values of specific heat are plotted as

functions of temperature. Tables of thermal properties are scattered throughout the literature; many sources, however, are contradictory. The accurate determination of specific heat and particularly of thermal conductivity at elevated temperatures is extremely difficult; therefore the values shown in the charts are to be considered as approximations only. The values presented in this text should suffice for preliminary calculations, but a proper literature search may still be necessary if a given problem is to be solved. See also the section on furnace walls (page 32 and Figures 21 and 22).

The boundary conductance depends on the nature of heat transfer. If two or more modes of heat transfer (radiation, convection, conduction) contribute to the heating of a piece, the respective conductances should be added. The conductance occurring in heat transfer by radiation has been dealt with in detail in Volume I; emissivity factors are shown in Appendix I of Volume I.

Determination of boundary conductance, h, for convection is rather uncertain. In most cases it may be assumed that air passes over an almost plane surface. In this case Equations (7) and (8) are recommended.[7] For velocities v_0 up to but not exceeding 16.5 ft per sec:

$$h = 1.087 + 0.225v_0 \tag{7}$$

For velocities v_0 above 16.5 ft per sec:

$$h = 0.524v_0^{0.78} \tag{8}$$

These equations are shown in Figure 18. Velocities are taken at standard conditions, not at the temperature of and the pressure in the furnace.

In some instances the flow of air can be considered to take place through a tube. This is applicable if the air flows through the charge, e. g., in the center of rings in bell type furnaces. In this case the value of h can be read from Figure 19. Air velocities in ft per sec (at standard conditions: 32 F; 29.92 in. mercury pressure) are plotted along the abscissa; various curves are applicable for different equivalent diameters, d, and the ordinate axis has three scales for h: one for air temperatures between 150 and 700 F, the next for air temperatures between 700 and 1400 F, and the last for air temperatures between 1400 and 2000 F.

The diameter, d, is expressed by an equivalent hydraulic diameter

$$d = 4A_c/p \text{ ft} \tag{9}$$

where A_c is the area of the cross section through which air is streaming (sq ft), and p is the part of the circumference through which heat is exchanged, expressed in feet.

[7] A. Schack, *Industrial Heat Transfer*. Wiley, New York, 1933.

The curves hold for a length of the air path of 5 ft. For a length of 1 ft all h values are to be multiplied by 1.08, for lengths of 10, 50, and 100 ft they are to be divided by 1.04, 1.12, and 1.18, respectively.

The curves are an approximate solution of equation 10,

$$h = \left(0.41 + 0.09 \frac{t}{1000}\right) \frac{v_0{}^{.79}}{d^{0.16} L_a{}^{0.05}} \tag{10}$$

This equation [7] is a modification of a summarizing empirical formula by Nusselt. The following notations are used: h = boundary conductance; t = temperature of air (mean of section); v_0 = velocity of air in ft per sec at standard conditions 32 F and 29.92 in. mercury pressure; d = equivalent diameter (see above); and L_a = length of air path.
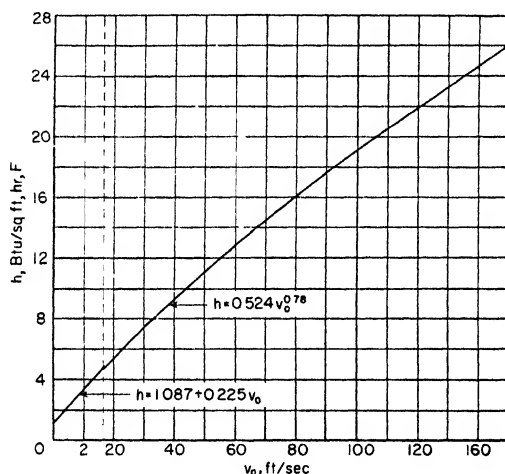
Fig. 18. Heat transfer coefficient (h) as a function of air velocity (v_0) at standard conditions. Air flowing over plane surface.

For either formula the determination of the velocity offers the greatest difficulty. The total volume of circulating air is known, and from the cross-section of furnace and charge the total free space can be found. But this method can determine only the mean velocity and not the velocity near the charge.

In case of heat transfer by radiation and convection combined, the two h values—for convection and radiation—are added. Heating by contact (transfer by conduction) must overcome a contact resistance, which is generally assumed to be very small. No figures on its magnitude are available.

For thin sections the heating time is predominantly determined by the boundary conductance; for thick sections the diffusivity becomes more important.

Some tests on heating aluminum strip (1 mm—0.04 in.—thick) in continuous annealing furnaces are a pertinent illustration. With a furnace tem-

$$h = (0.41 + 0.09 \frac{t}{1000}) \frac{v_0^{0.79}}{d^{0.16} L^{0.05}}$$
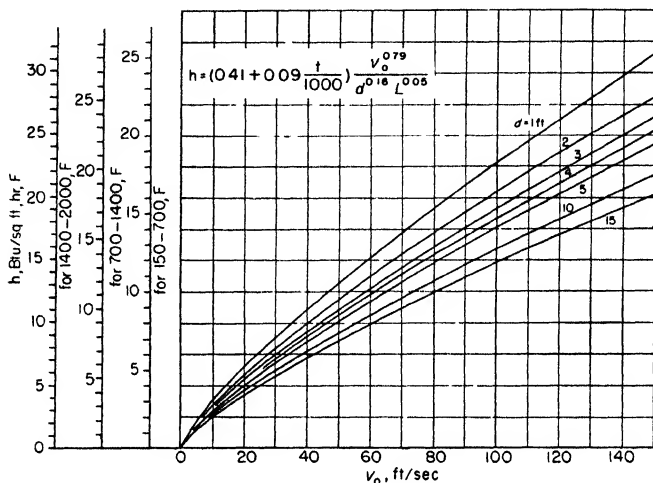
FIG. 19. Heat transfer coefficient (h) as a function of air velocity (v_0) at standard conditions for three temperature ranges and different hydraulic diameters (d). Air flowing through channel.

perature of 1470 F, heating times to reach 1100 F were in the order of magnitude of one minute.[8] The emissivity of aluminum is very low; therefore in order to improve heat transfer powdered charcoal was strewn on the strip. The temperature rise within the same time was sufficiently high to melt the aluminum. Heating bright copper in continuous strip annealing takes much longer than heating of oxidized brass (because of the higher emissivity of the latter).

FIG. 20. Charge consisting of a pile of small pieces.

In furnaces with protective atmospheres the gases may influence the heat transfer by radiation, e. g., circulating carbon dioxide has a higher emissivity than circulating air.

[8] H. Masukowitz, Z. Metallkunde, 24, 236 (1932). Observation of melting, personal communication.

F. Coils and Piles of Load

The case of single pieces has been treated so far, and in these the method of heat transfer (conduction, radiation, or convection) was of secondary importance, as exemplified by Figure 13. In many instances, however, furnaces are so loaded that a pile of pieces is heated. Figure 20 shows a typical charge of this kind. The individual pieces of the charge make but little contact with each other, and the contact is irregular and often unpredictable. Even such regular shapes as piles of sheets or coils of strip stacked one upon the other are complicated as far as thermal contacts from piece to piece is concerned.

When applying Figures 2 to 12 to such charges (piles, etc.), it is not permissible in calculations to use the thermal properties of the metal forming the charge. One can however conceive of the charge as being a single mass, having "apparent" properties different from the "true" properties of the material heated. If the charge consists for example of steel bolts,

Fig. 21. Apparent thermal conductivity of steel scrap.

the thermal conductivity includes the air spaces between the individual pieces and cannot be calculated. Figure 21 shows such a curve determined from experiments by Schack and Auhagen.[9] The temperature rise was measured; by using the Schack-Groeber charts [10] the conductivity was deduced based on a knowledge of the apparent density.

Finck [11] determined the apparent thermal conductivities of laminated brass; the plate method commonly used in measuring thermal conductivities of insulating materials was used here probably for the first time to determine the thermal conductivity of a "laminated metal." The results are discussed and compared with calculations and with the apparent thermal conductivity of steel, as found by Schack and Auhagen,[9] and by Paschkis, Doyle, and Finck.[12] The apparent conductivity for cartridge brass, 0.04 in. thick, is shown as a function of temperature in Figure 22.

The specific heat of such a pile of individual pieces or of laminated material is approximated sufficiently closely by the specific heat of the

[9] A. Schack and E. Auhagen, *Arch. Eisenhuttenw.*, 4, 469 (1930/31).

[10] A. Schack, *Industrial Heat Transfer*, Wiley, New York, 1933. See also H. Groeber, *Einfuhrung in die Lehre von der Warmeubertragung*, Springer, Berlin, 1926.

[11] J. L. Finck, "Symposium on Measuring Techniques," ASME annual meeting, New York, December, 1945. See also *Industrial Heating*, 12, 1132 (1945).

[12] V. Paschkis and J. A. Doyle, *Wire and Wire Products*, 21, 369 (1946). V. Paschkis and J. L. Finck, ASME Fall convention, Boston, September, 1946.

individual piece; the apparent density must be determined empirically. In general there is a certain relationship between the apparent density and the apparent thermal conductivity. Both increase and decrease in parallel, but not proportionately.

The influence of the method of loading on the heating time is discussed below. Different arrangement of piles in the furnace from that of individual pieces is necessary mainly in furnaces with heat transfer by radiation. To properly designed furnaces with forced air circulation and in salt bath furnaces this difference does not apply. The trend toward
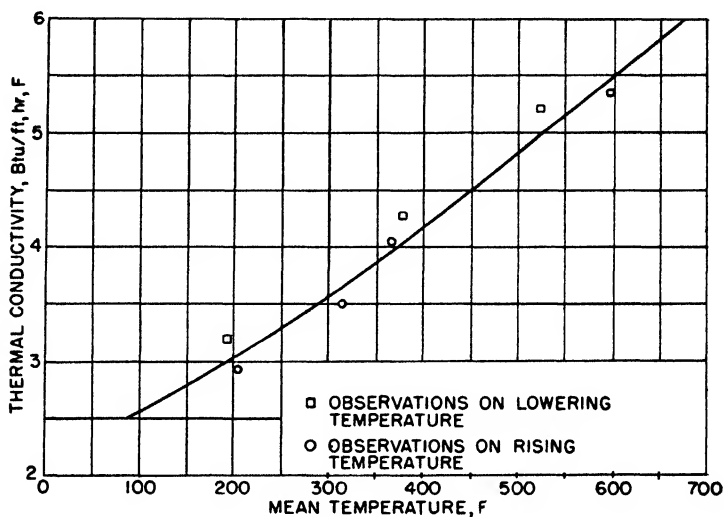
Fig. 22. Apparent thermal conductivity of brass sheets and coils.

increasing use of these two furnace types is therefore sound. The air stream, and salt, respectively, penetrate between the individual pieces. Rather than a large body with fairly low thermal conductivity, a small body (*e. g.*, of the size of an individual bolt) with high conductivity (*e. g.*, that of steel) is involved in the calculation of heating time in accordance with Figures 2 to 12.

The same applies to loosely wound wire coils. Salt, lead, or even air may penetrate between the individual layers, and thus the thickness which enters heat transfer calculation is that of the individual layer or wire. Piles of sheets, tightly wound wire, and coils of strip, however, are usually so tight that no air, salt, or lead would penetrate between the layers. For such coils and piles the method of loading is just as important in convection type furnaces as in radiation type (see also page 165).

G. Method of Loading. Furnace Size and Uniformity

From the preceding discussion, it becomes evident that the method of loading a furnace must influence considerably the temperature uniformity in the product obtainable within a given time of heating, and affect inversely the heating time necessary to reach a required degree of uniformity. Typical examples follow.

(1) *Piles of irregular pieces* such as bolts with heads, rivets, stampings, castings, etc. The proper way to heat such material, if heating in piles is acceptable, is in conduction or convection type furnaces. If for some reasons neither of these methods of heating can be applied and radiation furnaces must be used, the following considerations may be helpful (see Fig. 23).
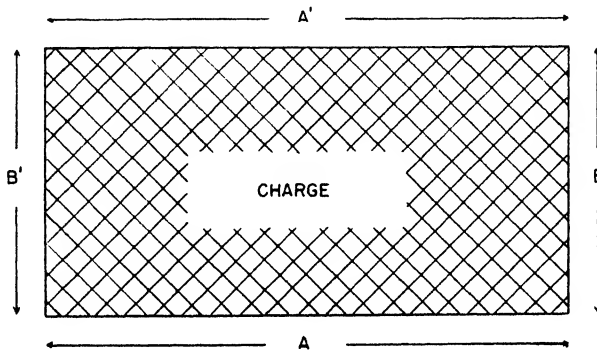
FIG. 23.   Directions of desirable heat flow.

If the charge fills a space of a square or if A is almost equal to B, and if the dimension A is large as compared with the size of the individual piece of the charge (*i. e.*, if the apparent density is small), heating must be very slow if any reasonable degree of uniformity is to be achieved. (Small temperature gradient between furnace and surface is essential.) Otherwise overheating of the outside pieces, particularly near the corners, is inevitable. Conditions improve if the square form is abandoned and one pair of sides (B,B') is made smaller. If this is done to any appreciable extent (a limit of $B = 0.75A$ may serve as example), the major part of the heat will be introduced to the charge from A and A'. In order to secure better uniformity the rate of heat generation on the surfaces facing B and B' and on the front and rear ends (not shown in the sketch) should be limited to the quantity necessary to cover the heat losses from the wall. Continuing this procedure to the limit results in a furnace loaded with two layers of pieces one on top of the other, and heated from top and bottom only. Such a furnace will heat in shorter time very much more uniformly. Should the decrease of heating time not be large enough to offset the loss in volume as compared with great height, then a larger hearth area becomes necessary, leading eventually to a continuous type furnace. This type of furnace should for example replace the customary car bottom type in foundry work.[13] If the pieces withstand tumbling, rotary drum furnaces

[13] V. Paschkis, *Am. Foundryman*, **10**. 81 (1946).

(see page 139) are preferable in which each piece of the charge comes in contact with the heated walls of the drum. If the charge consists of many pieces of identical size and shape (*e. g.*, bolts with or without heads) speed of heating and uniformity will be greatly augmented if the pieces are so arranged as to flow in an orderly way between heated surfaces (Fig. 24).
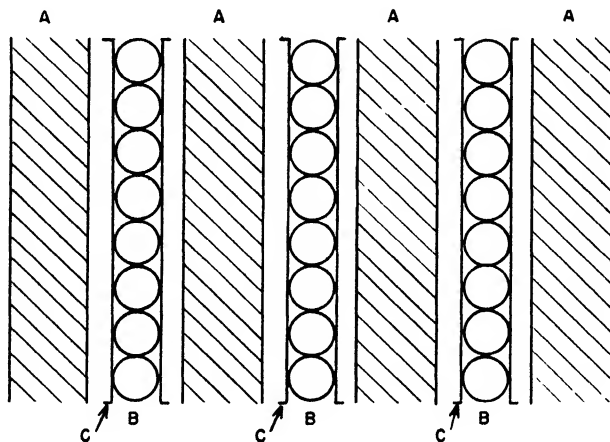
FIG. 24. Heating of bolts or tubes: *A*, heated walls (*e.g.*, embedded resistors); *B*, charge (bolts, etc.); *C*, guides.

(2) *Bars and tubes.* The best though unconventional method is to heat such shapes individually. It is customary to stack the pieces in piles of various height. In this arrangement the time for heating up to any reasonable degree of uniformity is increased and the rate of heating becomes nonuniform, the outer tubes or rods heating at a higher rate than the inner ones. The degree of uniformity for piles of tubes is increased if the sides of the furnace receive heat only at a rate sufficient to cover the wall losses and the tubes or rods are heated only from top and bottom.
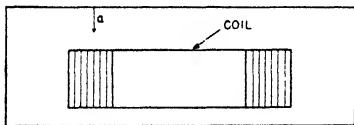
FIG. 25. Heating of piles of coils: *a*, desired direction of heat flow.

(3) For *strip and wire* the ideal method of heating and cooling is continuous in strands, rather than in coils. If heating in coils is required the following rules may be helpful.

(4) *Coils of strip.* The highest degree of uniformity is obtained in heating such coils either singly or two at a time, one on top of the other, in flat furnaces with top and bottom heat. If only top or only bottom heat is supplied, then not even two coils should be placed one above the other because the interface between them would prevent uniform heating of the coil farther from the heat source (*e. g.*, bottom coil in case of top heat, and top coil in case of bottom heat). With this heating method conduction takes place in the individual layers (see arrows in Fig. 25) and not across the minute airspaces, which are excellent insulators.

Except for strand annealing this is the only method by which an acceptable degree of uniformity can be achieved. The only disadvantage is the relatively high cost of handling. Because of the short heating times, relatively frequent changing of the charge is necessary, unless a continuous furnace is used. Heating times for one specific case are reported by Paschkis and Doyle.[14] Probably because of the necessity of frequently charging and discharging, such furnaces are often loaded with more than two coils one on top of the other. Uniformity is sacrificed in favor of cost. If several coils are thus piled up, the advantage of pure metallic conduction is lost.

In case of large coils, where one coil fills the entire cross section of the furnace chamber, such furnaces (bell type or pit type) will heat at least equivalent layers of each coil (all first layers, all second layers, etc.) relatively uniformly. Application of a core heater is then desirable.

To obtain the highest degree of uniformity possible with this arrangement, the core heater should be controlled separately, the thermocouple being located as close as possible to the load.

It is difficult to determine the exact desirable input rating for the center heater. But following a practical rule, it is advisable to put as much energy as possible in the inside heater. The least desirable heating arrangement for coils is to place them in piles in long box type or car bottom furnaces, or to load small coils in a bell or pit furnace, where several coils together are needed to fill the cross-section of the furnace. Here not even the entire circumference receives heat evenly; "heat shadows" are unavoidable, resulting in uneven heating.

(5) *Open coils of rod or heavy wire.* Liquid baths (salt or lead) are best if the coils are open enough to permit uniform cooling and even removal of the salt; next best are furnaces with forced circulation if means are provided to force the air through the windings of the coil and if the coil is loosely wound. Because of the high resistance to air flow between the windings, very high pressures would be needed. Heating in customary air circulating furnaces is not sufficient. The greatest part of the air would flow around the coil instead of through it. It is not possible to provide a heating arrangement yielding good uniformity in any type of furnaces with radiant heat transfer.

(6) *Closely wound wire coils.* If coils are wound so closely that neither air nor salt can pass, particularly if they are wound on spools, uniform heating can be approximated only by extremely slow heating. Although probably the thermal contact resistance between various layers is low, it certainly is still high enough to cause an appreciable lag of temperature rise of the inside as compared with the outside, unless very slow heating occurs. Best results obtainable with this method may be expected by placing the spools so that circulating air can reach the entire circumference. But it is essential to start heating with low air temperatures in order to cut down the temperature differences between the inside and outside.

(7) *Piles of sheets.* Contrary to a frequently encountered conception, it is not desirable to heat top and bottom, or even all four sides of such a pile. Only the longer sides of the sheets should be heated (see Figure 26). The desired direction of heating is indicated by arrows. Additional heat supply from the two short sides leads to overheating of the corners; heating from top and bottom overheats the outermost sheets. Again application of a small auxiliary amount of energy sufficient only to cover the wall losses of the furnace is desirable on the two short sides.

[14] V. Paschkis and J. A. Doyle, *Wire and Wire Products*, **21**, 369 (1946).

<center>H. BASIC DIAGRAM</center>

In the first volume a "basic diagram" was discussed in a general way (Vol. I, page 34). This diagram can be described more specifically for resistor furnaces. The basic diagram serves to determine the desirable furnace size and number of furnaces.

The first step in developing this diagram consists in determining the relationship between furnace dimensions and heating time. An increase of the heated dimension (*e. g.*, between arrows in Figure 26) causes an increase in necessary heating time; the increase takes place at a rate proportional to the first or second power of the heated dimension (doubling the heated thickness increases the heating time between two and four times). If an increase of volume is possible without increasing the heated dimension (*e. g.*, by piling sheets higher) the heating time does not change. (Curve 1 in Figure 19, Volume I, would be a straight line parallel to the abscissa axis.) If all dimensions—those in the direction of heat flow and those in other directions—are increased, the resulting shape of Curve 1 cannot be predicted in a general way. The tendency should be to make Curve 1 as flat as possible, by increasing the "non-critical dimension" in directions not subjected to heat flow.

FIG. 26.   Heating of stacks of sheets; *a*, direction of heat flow.

The next step is that of determining the number of furnaces necessary to give the desired output. If the heating time increases faster than the furnace volume (as is the case if the critical dimension alone is responsible for the increase in furnace volume), then a larger furnace volume calls for a greater number of furnaces—a striking proof against the erroneous attempt to increase blindly the furnace size. Only an increase in heated area with constant or even decreasing critical thickness results in a smaller number of necessary furnaces with increasing volume. This step must be repeated for each type or design which may be taken into consideration for practical reasons.

The third step consists in calculating the relationship between rate of heat loss and furnace size for each type. Large furnaces have in general a small relative heat loss (kw per unit volume). However, the relative heat loss changes with the shape of the furnace. If only one side of a furnace is extended the shape factor changes. If the shape of the furnace becomes very different (*e. g.*, is flattened considerably) the character of the rate-of-heat-flow *vs.* furnace-size curve may change appreciably.

The subsequent steps in developing the basic diagram need no separate discussion beyond the statements in Volume I.

I. Necessary Further Development

It may be observed that for single pieces temperature uniformity, rate of heating, heating time, and furnace temperature are well defined (page 3), but that for coils and piles of pieces almost only qualitative information was given (page 27). If this field is to be made more accessible to a rational approach, values of apparent conductivity have to be determined. It would be highly desirable to extend knowledge of the apparent thermal conductivities of various metals with different thicknesses of each layer, different pressure, etc. Values for tubes, rods in piles, and wire coils are not yet available. If such data were available, the entire field of heating time and uniformity would no longer be subject to vague and ill-defined statements but would be placed in the range of a rational approach.

Further investigations are necessary to determine the influence of changing thermal properties and furnace temperature on uniformity and heating time of the product. As long as no such systematic analytical investigations are available, it would be helpful to have a systematic compilation of empirical data on the size and shape of loads and required heating cycles. Investigations are needed to cover the practice of changing the furnace temperatures during the heating cycle. Finally, metallurgical and ceramic research are necessary to establish required degrees of final temperature uniformity and of rates of heating.

II. USEFUL HEAT

The "useful heat" of a furnace is the heat absorbed by the charge. In the previous chapter it was explained that the charge can never be expected to be at uniform temperature throughout. Hence the useful heat should really be determined by calculating the heat content of various parts (layers) of the charge, each part (layer) being heated to a different final temperature. For most practical purposes it is accurate enough, when calculating the useful heat, to neglect the temperature differences in the charge, and to work with only the surface temperature. That is, it is assumed that the entire charge is uniformly heated to a temperature which really is reached only at the surface. With this assumption and when heating does not proceed to the melting point, the useful heat can be found by multiplying weight of charge × specific heat × surface temperature.

The exothermic or endothermic heats of reaction incurred at phase changes are in the main not large enough to require consideration in this type of calculation.

If heating goes beyond the melting point the useful heat is found by multiplying weight of a charge × (specific heat of solid × melting tem-

perature + heat of fusion + specific heat of liquid × temperature difference between final temperature and melting temperature).

Values for specific heat can be taken from Figure 17.   It is important to note that the rate of useful heat flow changes with time.   Under normal conditions a large part of the total useful heat is supplied within the first part of the heating-up period of the charge, and gradually the rate of heat flow decreases to approach zero asymptotically.

Example.   A steel ball of 8-in. diameter, with a boundary conductance of 100 Btu per sq ft, hr, F, heated in a furnace of constant temperature, absorbs approximately in the first 36 sec 12%, in the first 180 sec 47%, and in the first 720 sec 92% of the total heat content of the ball at furnace temperature.   If the connected load is not large enough to supply this amount of heat, the furnace temperature drops and then returns slowly allowing only a gradual build-up of the heat content of the charge and thus imposing externally a limitation on the heating-up time.   If delay is to be avoided, sufficient connected load must be provided (see page 84).

III.   FURNACE PARTS

The design of resistor furnaces varies somewhat with the mode of heat transfer used in the furnace—radiation, convection, or conduction. In a first group, resistors—metallic or nonmetallic—are arranged on some or all of the walls; the energy to the load is transferred mainly by radiation and only in part by natural convection.   A variation of this design comprises resistors embedded in the furnace wall, the latter transmitting the heat by radiation to the charge.   In a second group, resistors are separated entirely from the charge; an air or gas stream passes over the resistors, absorbs their heat, and transfers the heat to the charge. In a third group the heat is transferred to the charge by conduction from a liquid bath—lead, salt, or oil—which in turn is heated either by external resistors or by passing current through the bath.   Furnace parts are discussed in the remainder of this section.   The design of some parts is the same for all three types of furnaces (Section A); others can be used only in one or two of the above-mentioned main types (Sections B, C, and D).

A.   Parts Used in All Three Types of Furnaces

1. Walls

The designing of walls consists in the selection of a one-, two-, or three-layer wall and then selection of material and thickness for each layer.   The design is influenced by three factors which are considered separately: the wall must have sufficient strength and stability; its design has considerable bearing on the thermal characteristics of the furnace and influences the accuracy of temperature control; and last but not least

economic considerations are involved. Often the requirements from these various aspects are conflicting and a compromise is sought.

(a) Wall Materials

The wall of any electric furnace contains at least in part thermal insulating material. For higher temperatures and for reasons of mechanical strength heavy refractory materials such as firebrick are sometimes used. Finally, metals are used as wall material.

The distinction between insulating and refractory materials becomes more and more vague, as the first are increased in refractoriness and the latter are made with higher insulating properties. The majority of insulation in brick form in use today is a class of refractories known as insulating refractories or insulating firebrick.

Nonmetallic wall materials are made in the form of bricks, blocks, monolithic material (cast concrete), and powder. The standard size of refractory and insulating brick is $4\frac{1}{2}'' \times 2\frac{1}{2}'' \times 9''$, although special sizes are also made. Blocks, particularly those made of light-weight insulating material, come in sizes up to $24'' \times 42''$ and in thicknesses ranging from $\frac{1}{2}''$ up to $4''$. Wherever the weight of such large shapes is within reasonable limits, there is a definite tendency towards increased use of blocks or larger size bricks because of savings in handling and the elimination of joints. However, it is advantageous from the thermal viewpoint to replace one layer of greater thickness by two thinner layers. A small air gap provides additional thermal resistance. Moreover, if several layers are used the joints can be staggered and thus joints connecting the inside of the furnace directly with the shell are avoided.

Monolithic material is cast into any desired shape and form at the time of constructing the furnace and is then dried and fired.

In former times it was customary to make the inside wall of any furnace of heavy firebrick if the temperature precluded the use of steel on the inside. The use of firebrick has been largely abandoned since insulating refractories have become available. The latter are made from silica- and alumina-bearing refractory clays, sometimes with addition of other material. Their high insulating value is achieved by making them artificially porous, usually by adding to the mix a filler material which burns out in firing.

As a rule the bricks are designated by a letter indicating the manufacturer and a number indicating the maximum permissible temperature in hundred degrees F. (Designation A 26, for example, means brick for 2600 F maximum temperature, made by manufacturer A.) There are bricks available for maximum temperatures of 2800, 2600, 2300, 2000, and 1600 F. Sometimes temperature limits are given by two figures: a higher one for "nondirect exposure" and a lower one for "direct exposure."

The lower limit is used because of the danger of spalling. Insulating bricks for lower temperature are either bonded or not but are generally not fired; for higher temperature they are usually molded and fired at elevated temperatures.

Insulating block is made of a mixture of asbestos fiber with basic magnesium carbonate or diatomaceous silica and usually calcined. The mixture is suspended in water and then dried—first mechanically, later by heating. Block without magnesia is usually recommended for temperatures up to 1900 or 2000 F, whereas material containing magnesia can be used for temperatures not exceeding 1000 F.

For low temperatures, such as those maintained in the use of ovens (450 to 500 F) insulation made of metal foil is sometimes used. A number of highly polished metal sheets (generally aluminum; recently copper has sometimes been recommended) are spaced at narrow intervals. Heat is transferred by radiation from one sheet to the next. Inasmuch as the spacing can be quite narrow without influencing the heat transfer, and the insulating value increases with the number of sheets, a highly efficient insulation can be built in a narrow space. The weight per unit volume of such metal insulation is exceedingly low, because the individual metal sheet is very thin.

In oven work the inside wall is usually made of steel. Insulation is put between the inside wall and the outside shell. The insulation, usually a light-weight type, has not in itself sufficient rigidity to hold the inside wall, and therefore the inside wall is connected to the shell by metallic reinforcements. These reinforcements form "thermal short circuits" (Vol. I, page 51) and should therefore be reduced to the minimum compatible with mechanical strength.

In modern design it is customary to build ovens and low temperature furnaces of self-contained wall units, frequently called "panels." Figure 119 (page 155) shows such a panel. In the design of such panels special emphasis is placed on avoiding "through metal" (metal connections) between the inside and outside metal covering. Almost all manufacturers have a special design for the solution of this problem, and the one shown here serves merely as an example.

(b) Strength and Stability

The most important properties of a wall are those related to strength and stability. Singly or combined, mechanical strength and chemical resistance are necessary; moreover, resistance to temperature changes is required.

Of these properties the chemical resistance is the least explored. Most insulating and refractory materials were previously used only in oxidizing atmosphere. With increasing use of protective atmospheres,

the behavior of such materials in reducing and neutralizing atmospheres becomes important.   Probably because of reduction of some of the oxides by the atmosphere, insulating and refractory material usually is considered to stand up to a lesser degree in reducing than in oxidizing atmosphere.   Stafford [15] reported that a group of "26" bricks (*i. e.*, bricks made for an operating temperature of 2600 F) were tested at 2200 F.   It was found that in oxidizing atmosphere the bricks stood up, but failed in some reducing atmospheres by deformation at loads below those known to be safe in oxidizing atmospheres.   Even small changes in gas composition seem to influence load-bearing capacities greatly.

A general rule-of-thumb to be used until more reliable data are available is that the permissible temperature of a brick or block should be reduced 300 F for material to be used in reducing atmosphere.

It is difficult to express mechanical strength by specific numerical values.   The "permissible stress of compression" is usually determined by rapidly increasing a load until failure occurs, whereas in practice a rather small load is applied permanently or for very long periods of time. Little if anything has been published concerning the limits of such small constant loads.   They are the more unpredictable because their effects are superimposed on phenomena of shrinkage and growth of wall materials; shrinkage and growth are independent of load.

The sidewalls of furnaces carry mainly their own weight.   In narrow furnaces having a flat refractory slab roof, the roof rests on the sidewalls, which then carry the weight of the roof in addition to their own weight. Arched roofs are generally supported by skewbacks.   Slow creep is most dangerous in the skewbacks and in the bottom of the furnace.   Here the weight of the load is generally carried.   Depending on temperatures, slab-roofs are generally limited to widths of 2 ft or less, arches to 15 ft or less.   For greater width (and sometimes even for widths below 15 ft) suspended roofs   either straight or arched —are used.   Figure 27 shows one such design.
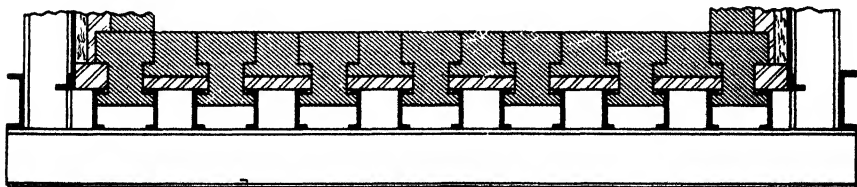
Fig. 27.   Suspended roof   (Courtesy *Intercontinental Engineers, Inc.*)

Strength of furnace structure is greatly influenced by the amount of mortar joints and the care with which the bricks are laid: the smaller the

[15] W. L. Stafford, "Symposium on Furnaces and Kilns," ASME semiannual meeting, Pittsburgh, 1944.

joints, the stronger the wall. Joints of $\frac{1}{2}$ in. are considered too large, and joints as low as $\frac{1}{16}$ in. or under can be made by careful workers. With the accurate sizing of the present-day insulating refractory, exposed walls are generally set up with the use of "air-set" type mortars of a thin consistency. The bricks are dipped in the mortar and rubbed into place. For "back-up" courses where bonding is unnecessary, the bricks can be set up dry without mortar.

Many manufacturers for reasons of strength hesitate to make the inside layer, whatever the material, less than $4\frac{1}{2}$ in. Now, as explained in Volume I (page 38), the materials of higher refractories are poorer insulators. Increasing the thickness of the better-conducting inside layer pushes the better-insulating material towards the outside, thus increasing the effective surface and hence the heat losses. This is an extreme example of sacrificing thermal efficiency for mechanical strength and shows the importance of investigating more carefully the field of mechanical strength in order to cut down the thickness of the inside wall.

In considering the application of any given material, shrinkage and growth are important.

Table I lists the mechanical properties of some refractory, insulating refractory, and insulating materials commonly used in furnaces.

TABLE I

MECHANICAL PROPERTIES OF SOME FURNACE MATERIALS

Manu-facturer[a]	Material	Crushing load (cold), lb/sq in.	Linear shrinkage		Reversible linear expansion		Density	
			Temperature, F	%	Temperature, F	%	lb/cu ft	Temperature, F
JM	85% magnesia	65–75[b]	600	1–2			13.0	600
A	A 16	175			1600	0.33	31.6	1600
B & W	B & W K16	48	1550	0.1[c]			18.8	
HW	HW 16	75–100	1550	2.0[c]			32.5	
JM	Natural	400	1600	1.4	1600	0.1	30	
JM	Superex	80–90[b]	1900	3.0			24	1900
A	A 20	175			2000	0.43	32.5	2000
B & W	B & W K20	95	1950	0.1[c]			25.3	
HW	HW 20	150–175	1950	2.0[c]			32.5	
JM	JM 20	115	2000	0.0	2000	0.5–0.6	35.0	
A	A 23	430			2300	0.63	47.1	2300
B & W	B & W K23	154	2250	0.6			25.9	
HW	HW 23	175–200	2250	2.0[c]			39.5	
JM	JM 23	170	2300	0.3	2000	0.5–0.6	42.0	
A	A 26	325			2500	0.68	48.0	2600
B & W	B & W K26	154	2550	0.4			41.6	
HW	HW 26	225–250	2550	2.0[c]			48.0	
JM	JM 26	190	2500	1.0	2000	0.5–0.6	48.0	

[a] JM, Johns-Manville; A, Armstrong; HW, Harbison Walker; B & W, Babcock and Wilcox.
[b] Insulating material; figure refers to compressive strength in lb/sq in. to compress $\frac{1}{8}$ in.
[c] Figure shown is the maximum.

Sudden temperature changes cause some materials to spall. Resistance against spalling therefore is important, particularly for materials used near the door or other openings, where an inrush of cold air causes rapid temperature drop. The ASTM has set up a standard testing procedure [16] consisting of the exposure of specified samples to definite temperature changes and counting the number of changes occurring before destruction of the brick.

(c) Thermal Design of the Wall

The various thermal characteristics of a wall result from the following properties of the material of each layer: thermal conductivity, specific heat, density, thickness, and sequence or arrangement of different materials if more than one are used. Moreover the boundary (or film) conductances on the inside and outside surfaces and frequently the connected load of the furnace per unit area are of importance.

For thermal conductivities see Figures 22 and 23 in Volume I. Values of density are included in Table I The figures in Table II give

TABLE II

SPECIFIC HEAT OF BABCOCK & WILCOX MATERIALS

Mean temperature, F	Specific heat, Btu/lb, F
500	0.210
1000	0.232
1500	0 248
2000	0.259
2500	0.269

as an example the specific heat values for some Babcock & Wilcox materials, holding for all.

The thermal design of a wall consists in selecting first one or several materials for one or more layers and then their respective thicknesses. The thermally desirable values must often be modified for mechanical strength. Then the problem remains of determining the thermal characteristics for the wall selected for mechanical reasons. The thermal design covers the questions of heat losses and of heating-up time. Usually it is desired to keep the heat losses low and the heating-up time short.

HEAT LOSSES

A change of wall thickness and/or material has at least two effects: it influences the first cost of the furnace and it changes the heat losses. The two changes are in opposite direction: an increase of thickness (of a given material) increases the first cost and decreases the heat losses. The

[16] ASTM Method C38–36.

effects can also be expressed in monetary terms, that is, by the cost per year necessary to cover the energy losses. Thus an increase in thickness causes an increase in first cost and a decrease in operating cost. Consequently there is an optimum thickness which yields the smallest over-all cost. In comparing several materials for a one-layer wall, the "economic thickness" for each material should be determined. The material with the thickness resulting in lowest over-all cost is thermally the best choice.

Consider first a single-layer wall, operated continuously. By referring to Figure 28, thickness may be plotted as abscissa, and cost per year as ordinate. One curve shows the heat costs; the other shows depreciation and interest on first cost, which increase with thickness. By adding the ordinates of the two curves for each value of the abscissa, the third curve- total cost- is found. This curve of total cost has a minimum, which occurs if the wall is built with the "economic thickness."

The line of depreciation and interest is curved because, for a given inside area of the wall, the volume of wall material increases more than proportionally to the thickness. The bend of the curve is steeper for small furnaces. For very large furnaces the line is almost straight or may even bend down slightly. The outside wall area, to which the reinforcements- steel shell, etc.- are proportional, does not grow in direct proportion to the thickness. Those reinforcements are in part responsible for the finite part, A, which the curve cuts off on the ordinate axis.
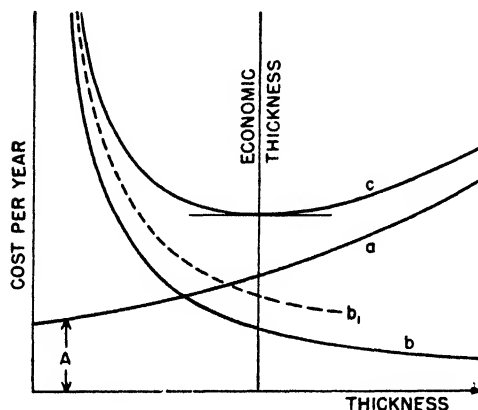
Fig. 28. Explanation of economic thickness: a, depreciation and interest; b, heat cost; c, total cost; $c = a + b$.

For large furnaces, in which the walls may be considered with sufficient approximation as infinitely long and wide, the heat cost—thickness curve is almost a hyperbola, as in Figure 28, curve b. It would be exactly a hyperbola but for the boundary conductance. For smaller furnaces the decrease of heat cost with increasing thickness is smaller than for large furnaces, because of the retarding influence of the shape factor (Vol. I, page 43). Curve b_1 is shown as an example for a smaller furnace.

McMillan [17] has developed a formula which permits determination of the economic thickness for large single-layer walls and continuous service.

For two-layer walls the problem becomes more complicated. If the thickness of one layer is determined by other than thermal considerations, *e. g.*, questions of mechanical strength, or the desire to have an inside wall of given thickness and material), the method is unchanged. If the thickness of both materials can be selected independently, then it is necessary to draw a chart (similar to Fig. 28) for various ratios of thicknesses of the two materials. An additional chart should then be drawn in which the minimum total costs are plotted against the ratio of the thicknesses. Frequently this curve will be lowest for a ratio of the thicknesses equal to zero, crowding out the higher conducting material. A minimum ratio may then have to be selected for mechanical reasons. A similar procedure should be followed for walls of three and more layers. However, for walls of two and more layers this procedure is economically justified only when very large furnaces involving large sums of money are concerned.

If the furnace is not operated continuously but is shut down at intervals, the annual heat cost decreases, the cost of depreciation is unchanged and therefore the optimum thickness is shifted to smaller values, and the minimum annual expense decreases. For noncontinuous operation the economic wall thickness can be determined by drawing a diagram similar to Figure 28. The heat losses can sometimes be read from charts with close approximation. Two cases of noncontinuous operation will be considered here. In the first a complete shutdown occurs after fairly extended periods of operation; the furnace is allowed to cool completely. The heat losses for the time of operation can be found approximately from: rate of steady-state losses × (time of operation + time of heating-up) + heat stored in the walls. The second case is that of regularly intermittent operation, say, heating the furnace for eight hours and letting it cool for sixteen hours. For such conditions—in fact for any intermittency—curves have been developed on the Heat and Mass Flow Analyzer. Some of these are shown in Volume I, Figures 34 and 35. A more complete report has been published by Bradley, Ernst, and Paschkis.[18]

HEATING-UP TIME OF FURNACES

The heating-up of a furnace occurs in different ways according to nature and size of the load. First the heating-up of an empty furnace is examined. In furnace practice it is customary to consider the heating-up period completed as soon as the temperature measuring or control instrument reaches the desired furnace temperature the first time. Such a

[17] C. B. McMillan, *Trans. Am. Soc. Mech. Engrs.*, **48**, 1269 (1926).

[18] C. B. Bradley, C. E. Ernst, and V. Paschkis, *Trans. Am. Soc. Mech. Engrs.*, **67**, 93 (1945).

definition is inadequate, and in this text the heating-up will be considered completed when the furnace walls are in temperature equilibrium. The conventional definition covers only one phase (A) of the heating-up process. Except for Table III-B (page 46) and the related text, it is assumed that load is introduced only after steady state has been reached—after the wall is in temperature equilibrium.
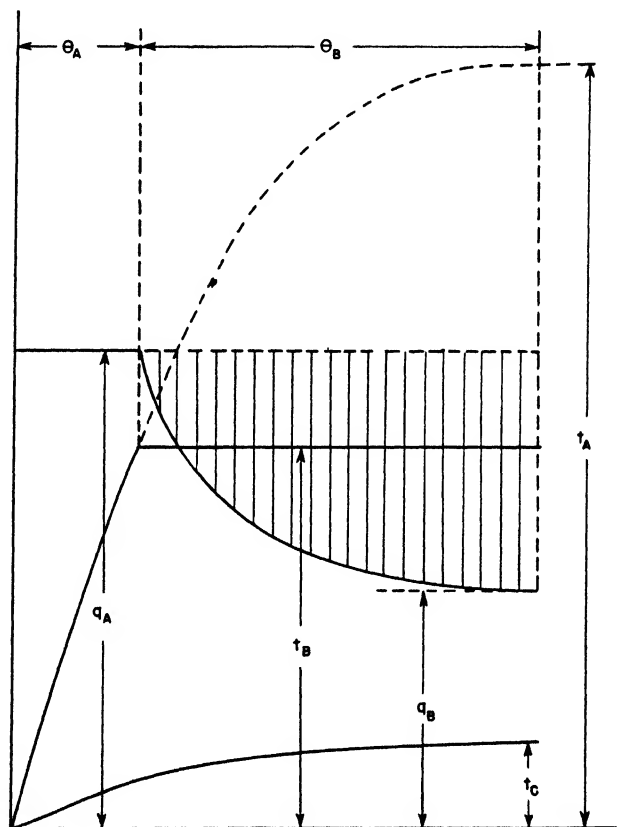
FIG. 29. Two phases of heating-up process.

Two Phases of Heating-Up Process. In connection with the heating-up, it is of interest to know the influence of initial rate of energy input (connected load) and wall design on heating-up time and power consumption. The heating-up process can be conveniently divided into two phases (referring to Figure 29)—phase A and phase B. During phase A the rate of energy input, q_A, is constant and equals the connected load. In this phase the temperature rises from the initial room temperature to the operating temperature, t_B. As soon as the furnace temperature

reaches t_B the heating-up process enters phase B. In this phase the furnace temperature is held substantially constant by the automatic temperature control. Or, more precisely, it oscillates slightly about the desired value of operating temperature. During phase B the rate of energy input is gradually decreased as the furnace wall heats up, until after a time, θ_B, steady-state conditions—for all practical purposes—are reached. The rate of energy flow, q_B, then equals the steady-state loss. The difference between the rate of input, q_A, and the rate at any instant during phase B is available for heating the load.

It should be noted that the rate of heat flow approaches the steady-state value, q_B, asymptotically: θ_B is theoretically infinitely long. Thus the total heating-up time is defined only when the desired approximation of the rate of heat flow to the steady-state value, q_B, is stated. It is, for example, possible to say that for practical purposes the steady-state value is considered reached and θ_B terminated when the rate of energy input is within 5% of the theoretical value q_B. If the steady-state loss is measured by determining the kwhr consumption over a given length of time, it will be found that the experimental values oscillate about the steady-state value. Small changes in the ambient temperature and/or in the boundary resistance as well as minor changes in the furnace temperature, caused by the operation of the automatic temperature control, account for these oscillations.

It is very helpful to examine what would happen if the temperature control did not begin to operate at the time θ_A, assuming that all furnace materials could withstand high temperatures without limit. Obviously the temperature would rise; and if $q_A/q_B = e$, and the thermal conductivity did not change with temperature, a steady-state temperature, t_A, would finally be reached such that $t_A = t_B \times e$. This temperature, t_A, is entirely fictitious because in practice the resistors would fail and the refractories would break down long before t_A is reached.

Example. Consider a furnace with a steady-state loss of $q_B = 10$ kw, an operating temperature, t_B, of 1800 F and a rate of energy input (connected load) of $q_A = 100$ kw. Then the fictitious temperature, t_A, would be $100/10 \times 1800 = 18000$ F.

In determining the length of heating-up time, the two phases A and B should be treated separately. It is obvious that the heating-up time, θ_A, will be shorter the higher the rate of energy input, q_A, compared with the final value, q_B; in other words, θ_A will be smaller for smaller values of e. This e can be called the excess ratio.

For single-layer walls composed of only one homogeneous material, it is possible to present in a single plot the entire phase A of the heating-up process for any set of conditions—any thickness, wall material, rate of

energy input, and boundary conductance.   Figure 30 shows such a plot.[19] Dimensionless times, $X_A = a\theta_A/L_H^2$, are plotted as abscissas and $1/e$ as ordinates, where a denotes the thermal diffusivity, θ_A the time of phase A, and L_H the thickness.   Several groups of curves are drawn, each holding for a different relative position n in the wall.   The hot surface is characterized by $n = 0$, the cold surface by $n = 1.0$, the midplane by $n = 0.5$, etc.   In each group several curves are shown, each of which holds for a different value of m, where m is the relative boundary resistance; $m = h/kL_H$.   Here h denotes the boundary conductance, k the thermal conductivity, and L_H the thickness of the wall.

Phase A is terminated as soon as the automatic temperature control cuts in.   This happens when t/t_A (ordinate in Fig. 30) reaches the value e. From this point on, the furnace temperature is held constant as the wall gradually heats up, until, after a time, θ_B, has elapsed, practical steady-state conditions are reached.

For each excess ratio, e, a graph can be drawn which gives all the necessary factors concerning phase B for any given set of conditions. Five such plots have been published.[19]   Such a graph, for $1/e = 0.2$, is shown in Figure 31.   The graph consists of two parts, both plotted over the same abscissa axis, which is in dimensionless units:

$$X_B = \theta_B(a/L_H^2)$$

where θ_B, a, and L_H have the meaning as explained above.   In the upper part, t/t_B is plotted as the ordinate; the arrangement of groups of curves for n and m is as explained for Figure 30.   No curves are shown for $n = 0$ because during phase B the hot surface is maintained at a constant temperature.

In the lower parts of the figure two scales are used on the ordinates: on one scale the rates of heat flow are plotted and are expressed in dimensionless units; every heat flow rate is given as the fraction of the steady-state heat flow rate necessary to maintain the temperature t_B.   For each value of m there are two curves, converging for $X_B = a\theta_B/L_H^2 = \infty$ at the value 1: one curve shows the heat flow rate entering the hot surface; this curve, at time zero, is larger than unity and gradually decreases to unity, while the other curve showing the heat flow rate from the cold surface to the surrounding atmosphere starts at a value smaller than one and gradually builds up to one.   On the second ordinate scale in the lower part of the chart, the total heat absorption on the hot surface and the total heat dissipation from the cold surface are plotted.   The two curves for each value of m show the integrated areas under the respective curves for heat flow rate.

[19] V. Paschkis, "Heating Up Time and Energy Losses of Furnaces," ASME semi-annual meeting, Pittsburgh, June, 1944.
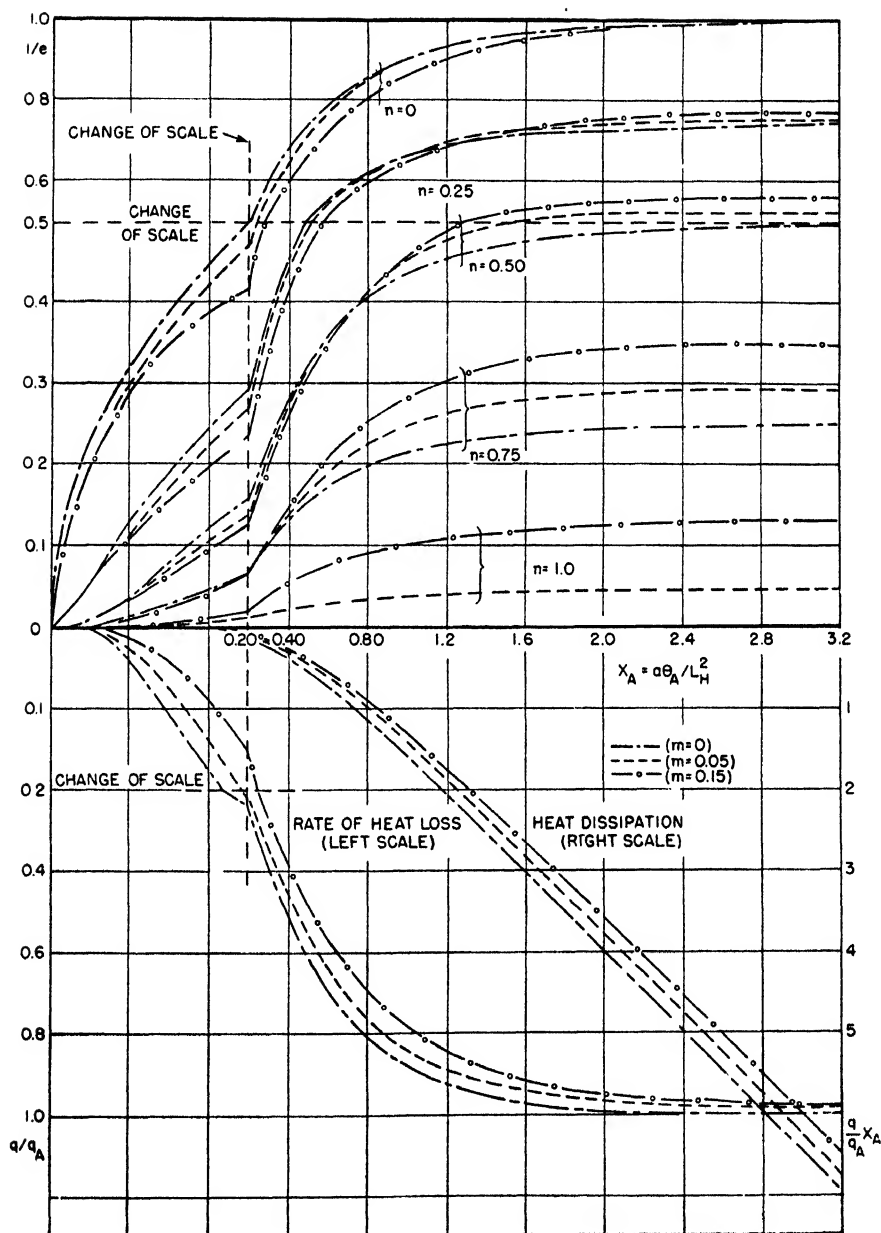
Fig. 30. Heating-up curve for phase A.

It would appear at first sight that the "heating-up period" is ended at the end of phase A, since at that point the desired operating temperature has been reached. Also in practice it is customary to speak only of phase A as heating-up period. However, a study of Figure 29 shows that at the end of phase A no surplus energy is available. The entire rate of energy input is used to cover the heat flow into the wall. If the load were introduced into the furnace at that moment, the temperature of the furnace would drop. The full amount of useful heat is available only at the end of phase B and after that continuously in steady state. Some part of the total rate of energy input, Q_A, is available for the heating of the load during the entire phase B. At first the available part is infinitely small, but it increases rapidly and approaches a constant value at the end of phase B. This available "useful" heat is indicated by the shaded area in Figure 29.

If at a given time after starting the furnace a greater amount of useful heat is desired than that indicated as available in Figure 29, a greater connected load must be applied (see page 85).

The graphs in Figures 30 and 31, since they are based on dimensionless parameters, make possible an analysis of the heating-up period of any furnace wall. The use of dimensionless parameters does not directly reveal the effects of a systematic variation in any one of thermal properties, such as conductivity, boundary conductance, thickness, etc. It is therefore proposed to examine, by means of examples, the separate influence of some of these variables, using the complete curves previously published.[19]

Influence of Individual Variables. *Connected Load.* From Figure 30 it is possible to determine the influence of the connected load on the length of phase A. In order to get a general curve the connected load may be expressed as a multiple of the rate of steady-state heat loss. (This multiple is equal to the excess ratio e.)

The heating-up time is expressed as a multiple of that time, which is obtained with $e = 10$. Figure 32 illustrates the relationship. Table III-A

TABLE III-A

HEATING-UP TIME (PHASE A)

Rate of input, Btu/sq ft, hr	Heating-up time, hr
1335	0.51
667.5	1.53
333.7	6.02
166.8	27.9

lists the times, in hours, for four different input rates required to heat a given furnace from an ambient temperature of 70 F to an operating temperature of
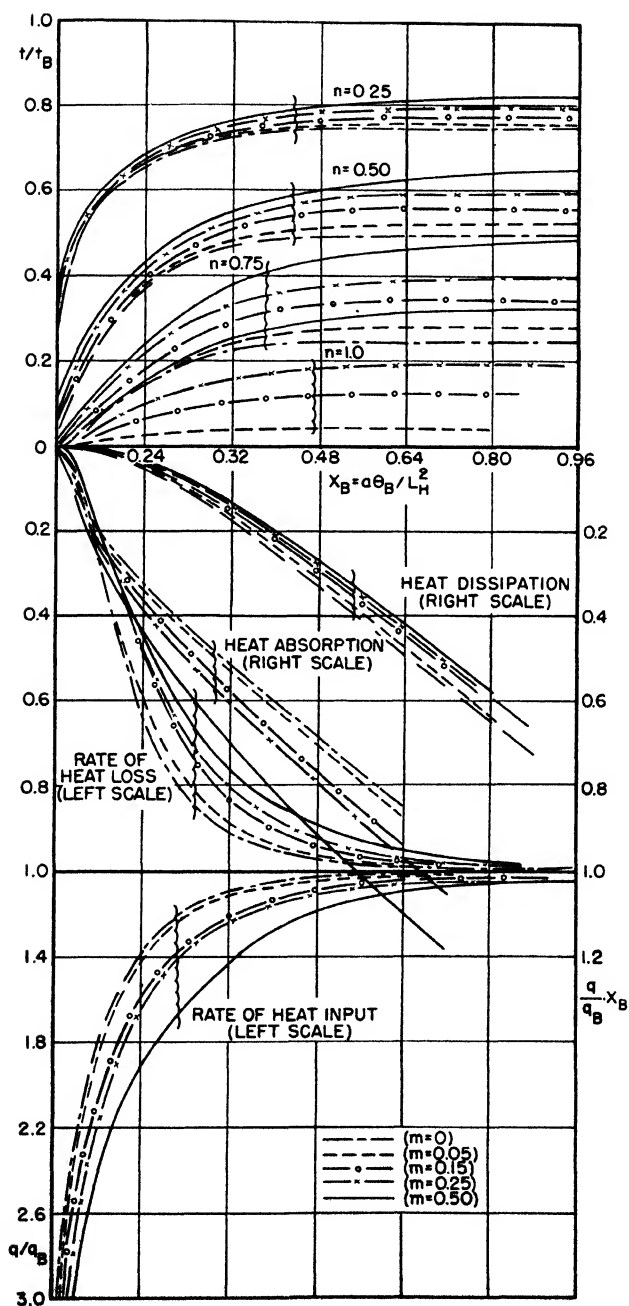
FIG. 31. Heating-up curve for phase B.

1570 F. These values were obtained from Figure 31, using the following assumed furnace properties:

Conductivity . . . . 0.07 Btu per ft, hr, F
Volumetric specific heat . . . . 5.25 Btu per cu ft, F
Boundary conductance . . . . 1.86 Btu per sq ft, hr, F
Wall thickness . . . . 9 in.

As explained above, at the end of phase A there is no "useful" heat available for heating the load; it is available only after a short interval, as shown in Table III-B. The table shows the amount of available useful heat at various
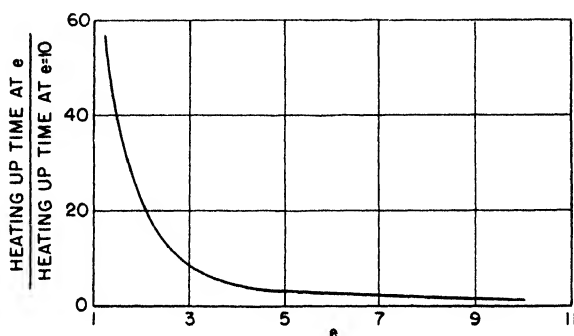
Fig. 32.   Heating-up time (Phase A) and connected load;
expressed by excess ratio e.

TABLE III-B

USEFUL HEAT FOR VARIOUS RATES OF ENERGY INPUT (PHASE A)

Rate of input, Btu/sq ft, hr	Maximum useful heat (Btu/sq ft, hr) available after					Max.	Calcd. from figure in ref. 19
	1 hr	2 hr	4 hr	10 hr	20 hr		
1335	802	974	1082	1171	1200	1201.5	8
667.5	0	133.5	387	494	526	534	7
333.7	0	0	0	147	195	200.2	6
166.8	0	0	0	0	0	33.4	5

times after starting the furnace; in the next to the last column the values which can ultimately be obtained are given. Thus it can be seen that, in order to have the maximum available useful heat, a higher connected load may be desirable.

An additional question arises concerning the influence of the connected load on the total heating-up time, including both phases A and B. Figure 33 answers this question in a general way. Values of $1/e$ are plotted as abscissas; heating-up times, expressed as multiples of the value at $1/e = 0$, are plotted as ordinates. The expression $1/e = 0$ or $e = \infty$ indicates infinite excess ratio; this, in turn, means that the inside surface reaches the control temperature,

t_B, immediately. This curve is based on the assumption that "steady state" is reached when the rate of heat loss is within 4% of the theoretical steady-state loss. The figure shows that the total heating-up time (phases A and B) is not greatly influenced by the connected load.
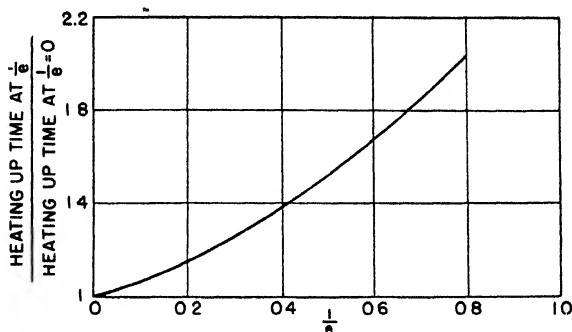
Fig 33   Total heating-up time and connected load, expressed by excess ratio e.

Referring again to the example of the 9-in. wall, the figures in Table IV can be given for the total heating-up time (phase A + phase B, the latter to within 4% of the steady-state loss).

TABLE IV
TOTAL HEATING-UP TIME (PHASES A AND B)

Rate of energy input, Btu/sq ft hr	Heating-up time, hr
166.8	37 0
333 7	24.8
667.5	21.3
1335	19 3
Constant temperature [a]	18.1

[a] Refers to the case in which the inside surface reaches operating temperature immediately

Thermal Conductivity. Walls with different conductivities will of course have different heating-up times and energy losses.   Conductivity has a threefold influence: the value of dimensionless time X_A, read on the abscissa, changes, because diffusivity a includes thermal conductivity; the value of m changes ($m = k/hL_H$); and finally the value of e changes.

This latter fact becomes clear if it is recognized that a change in conductivity will change the thermal resistance of the wall and therefore, for a given rate of energy input, q_A, will also change the fictitious temperature, t_A.   Inasmuch as t_B is unchanged, a value of $e = t_A/t_B$ different from that of the old conductivity will apply.

If, for the wall discussed above (see Table III), the conductivity is changed to 0.05, 0.10, and 0.14 Btu per sq ft, hr, F, the readings on the charts [19]

must be taken for different values.   The readings are tabulated in Tables V and VI.   Table VII shows the heating-up time (phase A) for these conditions.

TABLE V

CHANGE OF PARAMETERS WITH k

k, Btu/ft, hr, F	a/L_H^2	m	q_B at $t_B = 1570$ F (70 F ambient)
0.05	0.0169	0.0358	96.5
0.07	0.0237	0.05	133.5
0.10	0.0339	0.0716	186.5
0.14	0.0484	0.100	255.0

TABLE VI

VALUES OF e FOR DIFFERENT INPUT RATES AND k VALUES

Input rate, Btu/sq ft, hr	Value of e for k, Btu/ft, hr, F =			
	0 05	0 07	0 10	0 14
166.8	1.725	1.25		
333.7	3 45	2.5	1.79	1.308
667.5	6.90	5.0	3.58	2.62
1335	13.80	10.0	7.16	5.24

TABLE VII

HEATING-UP TIME FOR WALLS OF DIFFERENT CONDUCTIVITIES

Input rate, Btu/sq ft, hr	Heating-up time (hr), for k, Btu/ft, hr, F =			
	0 05	0 07	0.10	0.5
166.8	17.85	27.9		
333.7	4.17	6.132	9.16	13.5
667.5	1.07	1.52	2.36	3.16
1335	0.366	0.500	0.59	0.78

Where no times are shown (first line, last two columns), the rate of energy input is not high enough to bring the furnace to a temperature of 1570 F.

Volumetric Specific Heat.   A change in volumetric specific heat influences only the reading on the abscissa axis, that is, it will influence only X_A.   By taking the same wall which is used for Table III-A, but changing the volumetric specific heat, the heating-up times for phase A can again be computed.   They are directly proportional to the volumetric specific heat.

For a volumetric specific heat of 10.5 (instead of 5.25 as in the wall for Table III-A) the heating-up times become, for the input rates shown in Table III-A, 1.02, 3.06, 12.04 and 55.8 hr, respectively.

Wall Thickness. Contrary to steady-state conditions, the wall thickness has much less influence than the conductivity. Conductivity and wall thickness influence both m and e equally. Since the thickness enters in its second power in the reading of the abscissa whereas the conductivity enters only in the first power, a great influence of wall thickness might be expected. The small degree of influence exists because only a thin layer near the surface participates in the heating-up process.

Walls with relatively large thickness heat up (as far as phase A is concerned) like a semi-infinite solid. The value of thickness, L_H^*, beyond which the heating-up time, θ_A, for phase A is independent of a further increase in thickness, depends on the thermal conductivity of the wall, the rate of heat flow, and the temperature to be achieved, and is expressed by:

$$L_H^* \geqq 1.98 \frac{kt_B}{q_A} \tag{11}$$

The heating-up time for walls with thickness larger than L_H^* is expressed by:

$$\theta_A = \left(\frac{t_B}{q_A}\right)^2 \frac{kc\rho}{1.28} \tag{11a}$$

This equation applies to most practical cases, because with any customary wall material the value of L_H^* is only a fraction of an inch. A further obvious condition that must be satisfied is that q_A be larger than the rate of steady-state heat loss, q_B.

Example.

$$
\begin{aligned}
k &= & 0.8 \text{ Btu per ft, hr, F} \\
c\rho &= & 20 \text{ Btu per cu ft, F} \\
L_H &= & 9 \text{ in.} = 0.75 \text{ ft} \\
t_B &= 1500 \text{ F} \\
q_A &= & 1.5 \text{ kw per sq ft} = 5100 \text{ Btu per sq ft, hr}
\end{aligned}
$$

What is the heating-up time, θ_A, for phase A?

(*1*) Steady-state heat loss is $(1500 \times 0.8)/0.75 = 1600$ Btu per sq ft, hr, which is smaller than 5100 Btu per sq ft, hr; hence equation (11) may be used:

(*2*)
$$1.98 \times \frac{0.8 \times 1500}{5100} = 0.466 \text{ ft}$$

$$0.466 \text{ ft} < 0.75 \text{ ft}$$

Hence, equation (11a) may be used to determine θ_A:

$$(3) \qquad \theta_A = \left(\frac{1500}{5100}\right)^2 \times \frac{0.8 \times 20}{1.28} = 1.08 \text{ hrs}$$

In the example a very small connected load ($q_A = 1.5$ kw/sq ft) is used, because thus the significance of Equation (11) is made clearer. With a greater and more practical value of q_A, e. g., ten times as large or 15 kw/sq ft, the critical value would be ten times as small, or 0.0466 ft. The thickness could be selected at any practical value without a change in the heating time for a given value of q_A.

Previous experiments of the author [20] tend to indicate that in two-layer walls only the inside layer need be considered when studying phase A of the heating-up process. Calculation of heating-up with load is complicated by the fact that the amount of energy available for the wall depends on the ability of the charge to absorb heat. A load consisting of thin pieces with large exposed area absorbs heat rapidly, leaving less for the wall; wall and charge will heat up together. On the other hand, if the charge consists of very heavy bulky material and the heat transfer to the charge is poor, the charge temperature may lag considerably behind the furnace temperature. No general curves are as yet available to show on a rational basis the influence of the charge on the heating-up process of the wall, and the resulting temperature rise in the charge.

2. Furnace Shell

The furnace walls consist of one or more of the following materials: refractories, insulating refractories, and insulation; the walls are contained in an outside shell   With very few exceptions, a steel shell with or without structural reinforcements is used, but in a few cases the wall proper is contained in an outer wall of red brick work. In the latter case heavy structural reinforcements are used, consisting of I or U beams, connected by a system of tie rods.

The steel shells are made of stock of various thicknesses, according to the size of the furnace and to the amount of structural reinforcements used. The design of the shell is also influenced by the manner of shipment. If the furnace is shipped complete, with lining and resistors in place, the shell may have to be heavier than that of a much larger non-portable furnace, which is assembled in the user's shop. The shells may be welded or joined by rivets or bolts. When bricks are layed wet it is desirable to have one side of the casing, preferably the roof, detachable, in order to allow the water vapor to escape and thus dry the lining. Furnaces operating with protective atmosphere should have a gastight

[20] V. Paschkis, "The Significance of Proper Selection of the Connected Load in Resistor Furnaces," First International Congress for Electrothermics and Electrochemistry, Scheveningen, Netherlands, 1936.

shell. Because of the danger of welds bursting open under the stress of expansion, bolted joints with gaskets are preferable.

Because of expansion of the lining, the tie rods must not be too rigid; they can be made springy either by actually tightening them against springs or by pressing the tightening nut against soft material such as wood.

For ovens and furnaces operating at low temperatures, shell, insulation, and inside wall are frequently built integrally as units (see page 155).

3. Temperature Control

With the exception of some very small laboratory furnaces, the maximum rate of energy input into a resistor furnace always exceeds the rate of steady-state heat loss. If no control were applied, the temperature of a furnace would increase, until the rate of heat loss at some higher temperature equals the rate of input (phase A, temperature t_A, page 40).

The control can be automatically or manually operated; another classification of control refers to the means of decreasing the energy consumption: the connected load can be lowered or the full connected load can be applied in intervals instead of continuously. Means of lowering the full connected load include lowering the voltage or changing the connections of resistors so as to change the over-all resistance of the heaters (e. g., by putting two resistors in series).

(a) Methods of Decreasing Mean Rate of Energy Consumption

LOWERING OF CONNECTED LOAD

One way to change the input voltage consists of applying a transformer (autotransformer; transformer with separate windings and taps on primary or secondary; transformer with movable core). Transformers with movable core are desirable because they allow continuous change of input rate instead of a change in steps. Their use, however, is limited by their high first cost; autotransformers rather than transformers with separate windings should be used, unless the input voltage is so high that operation of the furnace becomes unsafe.

In selecting the taps of transformers no special rules prevail. Taps will usually be so selected that the power is changed in equal steps. There are special cases, however, where the transformer is used mainly for compensating the change in heater resistance because of aging; then the total voltage range is conveniently divided into steps of equal voltage (see page 83). Less expensive autotransformers result if voltage ratios between primary and secondary of approximately 0.6 to 0.86 are avoided. Additional savings result if all voltage ratios above 0.6 can be avoided.

Proof.[21]   Generally, autotransformers for a given output are smaller if the voltage ratio, G_v, approaches unity. The constant value of the furnace resistor however causes a second trend, decreasing the size of the transformer with increasing value of G_v. Interaction of the two trends results in a less economical range of voltage.

Notations. N_E = turns of the winding, G_v = voltage ratio = N_{E_s}/N_{E_p} = I_s/I_p, E = voltage, and I = current. Subscript p indicates a value pertaining to the primary, subscript s to the secondary. In first approximation the size of the core of an autotransformer can be considered constant; it must be sufficiently large to carry the necessary magnetic flux for the primary voltage. Then the cost of the transformer is proportional to the losses in the windings. The total losses in the windings are:

$$\Sigma(I^2 N_E)^2 = N_{E_s}(I_s - I_p)^2 + (N_{E_p} - N_{E_s})I_p^2 \tag{12}$$

If the voltage ratio, G_v, of the autotransformer is 1, then a current, I_f, would be flowing:

$$I_p = I_f(N_{E_p}/N_{E_s})^2 \tag{13}$$

The current, if flowing in the primary, would cause losses expressed by:

$$I_f^2 N_{E_p} = I_p^2 \left(\frac{N_{E_p}}{N_{E_s}}\right)^4 N_{E_p} \tag{13a}$$

By combining Equations (12) and (13a):

$$\frac{\Sigma(I^2 N_E)}{\Sigma(I_f^2 N_{E_p})} = \frac{N_{E_s}}{N_{E_p}}\left(\frac{N_{E_s}}{N_{E_p}}\right)^4\left(\frac{I_s}{I_p} - 1\right)^2 + \left(1 - \frac{N_{E_s}}{N_{E_p}}\right)\left(\frac{N_{E_s}}{N_{E_p}}\right)^4$$

By substituting for $I_s/I_p = N_{E_s}/N_{E_p} = G_v$:

$$\Sigma \frac{I^2 N_E}{I_f^2 N_{E_p}} = G_v{}^3 - G_v{}^4 = C \tag{14}$$

where C is a modulus for the size of the transformer—the larger C, the more expensive the transformer. By differentiation one can find that C has a maximum: for $G_v = 0.75$, $C = 0.104$. In Figure 34, C is plotted as function of G_v. It is evident that it is advantageous to avoid values of G_v between perhaps 0.6 and 0.86.

Of the N_{E_p} turns of an autotransformer, $N_{E_p} - N_{E_s}$ turns have to be wound for a current I_p and the remaining N_{E_s} turns for a current $I_s - I_p$.

In Figure 35, I_s, I_p, and $I_s - I_p$ are plotted against G_v. If an autotransformer is wound for, and has a tap at, $w = 0.5$, then taps can be applied at any value $0 < G_v < 0.5$ without further check of the size of turns.

Tap-changing switches are usually made for switching without load.

Control resistors connected in series with the heating unit are used only for very small units, because the resistors absorb energy at the rate of the difference between the connected load of the furnace and the momentary demand. The current passing through these control resistors absorbs part of the available voltage and leaves only the remainder for the furnace.

[21] V. Paschkis, *Elektrowärme*, **1**, 33 (1931).
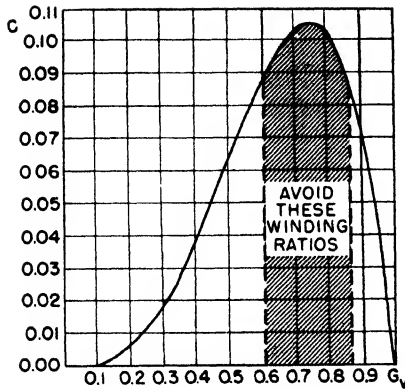
FIG. 34. Values of modulus C in an autotransformer as functions of winding ratio G_v (indicating undesirable range of the latter).
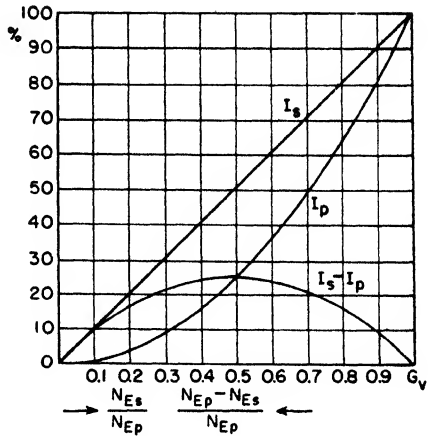
FIG. 35. Auto transformer size and ratio of windings.

On a similar principle, part of the voltage can be used up in either reactors or condensers. The latter method is not frequently applied because of the high cost. Inductances are relatively inexpensive and do not absorb an appreciable amount of energy (Fig. 41). Their disadvantage is the lowering of the power factor. Reactors are, however, of considerable importance when they are so made as to change their im-
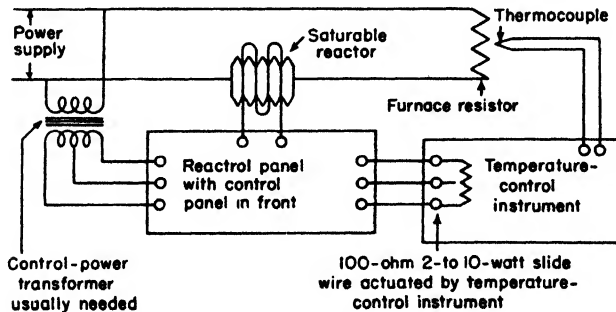
FIG. 36. Temperature control with saturable reactor.
(Courtesy *General Electric Company*.)

pedance continuously rather than in steps. The most commonly applied design involves a reactor with core; the change in inductance is provided by greater or smaller saturation of the core by direct current. Figure 36 shows a wiring diagram of a control incorporating this method. The amount of direct current governing the impedance of the "Reactrol" is regulated by an automatic temperature controller and may be changed continuously without steps.

Finally, the connected load can be decreased by changing the internal connections of resistors. Theoretically this can be done in almost unlimited steps. Practical considerations, particularly of resistor design, limit this method to a few combinations, some of which are shown in Figures 37 to 40.

In all the combinations shown the electric phase load remains unchanged in all positions. In Figures 37 and 38, all resistors are loaded uniformly in every position, although to a different amount. In Figures 39 and 40, however, some resistors are disconnected in some positions. If the resistors are not spaced appropriately (mixing the locations for each group, so that adjacent resistors always belong to different groups), the resulting heat generation is too spotty.

DECREASING EFFECTIVE TIME OF HEATING

As stated above, another way of adjusting the energy absorption of a furnace is that of reducing the time during which the energy (at full rate) is applied. This reduction of time can be done simply by switching the furnace on and off by hand. But such control would be very inaccurate and is of course out of the question (except perhaps rarely with laboratory furnaces) because of the labor involved. However, the switching can be effected by an automatic device which connects and disconnects the furnace at regular intervals. Such controllers yield regularly successive "on" and "off" periods. Moreover, the total length of the period (on + off) as well as the ratio of the times on/off may be adjusted.
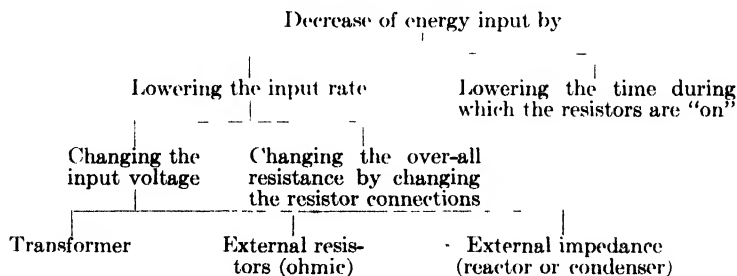
The following table summarizes the means of control.

Decrease of energy input by

Lowering the input rate		Lowering the time during which the resistors are "on"
Changing the input voltage	Changing the over-all resistance by changing the resistor connections	
Transformer	External resistors (ohmic)	· External impedance (reactor or condenser)

(b) Modes of Control

There are several methods of control in use for electric furnaces: two-position control, proportional control, derivative floating control, and second derivative control are some of the most important.

In a two-position control the energy supply changes at short intervals between two fixed values of input rate. If the lower value of input rate equals zero, the control is called "on-off control." In electric furnaces the two-position control is the only means possible without complicated auxiliary apparatus.
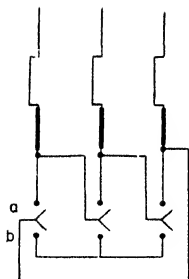
FIG. 37. Delta-Y connection of resistors.

Position	Designation	Connected load
a	Δ	100%
b	Y	33⅓%
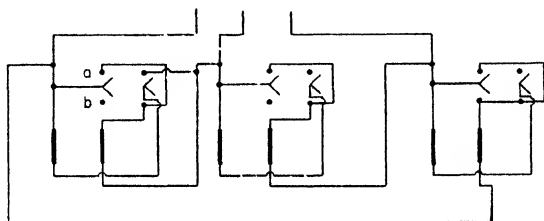
FIG. 38. Series-parallel connection of resistors.

Position	Designation	Connected load
a	Parallel	100%
b	Series	25%
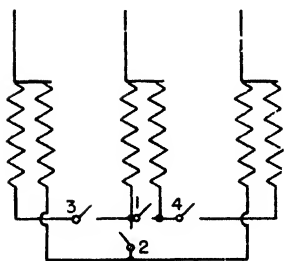
FIG. 39. Wiring diagram for double-Y connection.

Connections	Load	Switches	In or out
‖ Y	100%	1, 2, 3, 4	In
¦ Δ	75%	1, 2	Out
¦ Y	50%	1, 3, 4	Out
¦ Y	25%	more switches would be necessary	

‖ = two circuits parallel   Δ = delta connection
¦ = two circuits in series   Y = Y connection
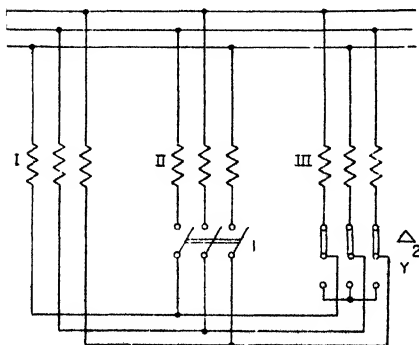
FIG. 40. Decreasing connected load.

Switch 1	Switch 2	Load
In	Δ	100%
In	Y	66⅔%
Out	Δ	50%
Out	Y	33⅓%

Specific load of resistors	Resistor groups in circuit
100%	I, II, III
100%	I, II
75%	I, III
100%	I

All other modes require a continuous change of input rate (for example, by means of variable inductances); this may be approximated by a large number of steps of input rate, obtainable by transformers with a large number of taps.

In proportional control, various input rates are definitely related to certain temperatures; if the load in the furnace changes, the controlled temperature changes too. Therefore, proportional control is undesirable for resistor furnaces.

In derivative or floating control, the change of rate of input starts as soon as the temperature deviates from the desired value. The change of input rate is proportional to the rate of change of temperature and continues at constant speed (single-speed floating control) or at variable speeds, according to the amount of deviation from the desired temperature (double- or triple-speed floating control).
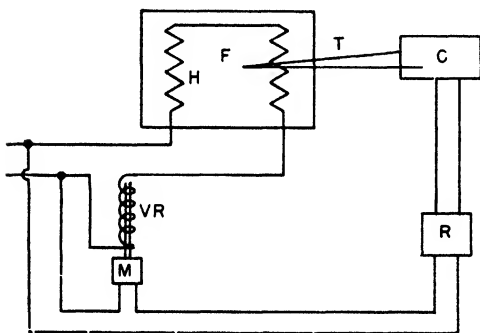
Fig. 41. Circuit for derivative control: *C*, control instrument; *F*, furnace; *H*, heater; *M*, motor; *R*, relay; *T*, thermocouple; *VR*, variable reactance.

In the second derivative control, the change of rate of input is altered with the change of rate of the change of rate of temperature deviation with time.

A number of combination controls are available. For example, Figure 41 shows schematically a derivative or floating control. For details concerning various modes of control, reference is made to special literature.[22]

(c) Control Instruments

The measuring device for low temperatures consists of mercury thermometers (available for temperatures up to 1000 F, approximately). For higher temperatures resistance thermometers are sometimes used;

[22] Of the numerous publications, a few references are given at random: C. O. Fairchild in *Temperature, Its Measurement and Control in Science and Industry*, Reinhold, New York, 1941, p. 587; J. C. Peters and T. R. Olive, *Chem. & Met. Eng.*, **50**, 98 (May, 1943); D. P. Eckman, *Principles of Industrial Process Control*, Wiley, New York, 1945; J. C. Peters, *Trans. Am. Soc. Mech. Engrs.*, **64**, 247 (1942); C. E. Mason, *ibid.*, **60**, 327 (1938); C. O. Fairchild, *Instruments*, **13**, 334 (1940).

they are made of materials with a high temperature coefficient of electric resistivity, such as nickel or platinum. The most commonly used measuring device in industrial furnaces is the thermocouple, consisting of two wires (legs) of different material. The metals used for the legs are selected according to the operating temperatures. Standard combinations are: for temperatures up to 1400 or 1500 F, iron and constantan; up to 1900 or 2000 F, chromel and alumel; and above 2000, platinum and platinum-rhodium.

The wires are sometimes directly exposed to the furnace, sometimes (particularly when operating at high temperatures and/or with protective atmosphere) enclosed in protection tubes. These tubes should, for the sake of accuracy, be as light as possible. Metal protection tubes are preferable, although in special cases, particularly for immersion in salt and lead baths, double tubes (ceramic inner tube protected by a metallic outer tube) are used. A recent development provides a transparent protection tube which results in high accuracy.[23] The measuring device transmits its findings to the control instrument proper; mercury thermometers transmit their measurements mostly by means of a compressed gas (air or nitrogen) to a manometer (pressure gage). Ohmmeters or potentiometers are used together with resistance thermometers. Thermocouples are the most commonly employed measuring device. A large variety of instruments have been developed for use with thermocouples. Since they generate a potential difference between the hot (welded) end of the wires and the cold end, any instrument capable of measuring voltage can be applied. Iron and constantan couples generate a voltage in the order of magnitude of 2.75 mv per 100 F temperature difference, chromel and alumel 2.00 mv per 100 F, and platinum and platinum-rhodium 0.5 mv per 100 F.

The voltages can be read either on millivoltmeters or on potentiometers. The former should have an internal resistance of several hundred ohms in order to eliminate errors due to the resistance of the couple and leads; they are less expensive than potentiometers but are also less accurate. The principle of the potentiometer control is shown in Figure 42. Transmittal of signals from the control instrument to the resistor is initiated by contacts. Inasmuch as the pointers of temperature control instruments are not strong enough to insure good contact, one of several auxiliary devices is used. Figure 43 shows a clamping bar arrangement, Figure 44 an electronic device. In potentiometer-type instruments the contact arrangement is entirely independent of the pointer contacts.

The contacts of the control instrument transmit the commands gaged by the measuring device to the power changing devices. In many

[23] J. P. Vollrath, *Ind. Heating*, 11, 1619 (1944).
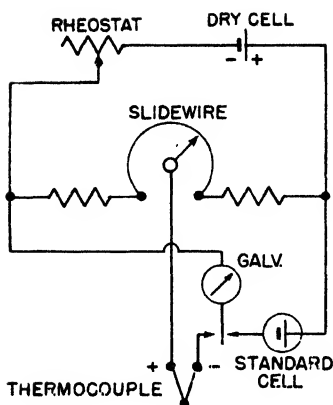
FIG. 42. Principle of potentiometer control. (Courtesy *Leeds & Northrup Company*.)
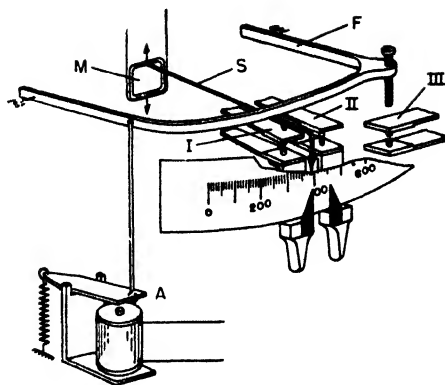
FIG. 43. Clamping bar arrangement for temperature control. *S* pointer; *M* magnet; *F* clamping bar. I Min. contact; II Max. contact; III limit contact (end of scale); A solenoid.
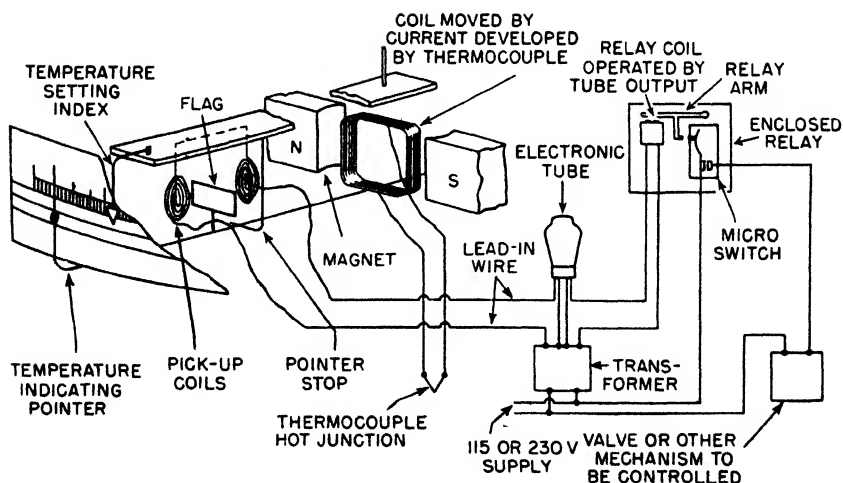
FIG. 44. Electronic temperature control. (Courtesy *Wheelco Instruments Company*.)

instances these are contactors of customary design. Because frequent switching is necessary it is well to select extra heavy types.

Other instruments act through a motor or an electronic tube which changes the position of a movable core or influences the saturation of the reactor.

(d) Accuracy of Control

The accuracy of control influences only temperature "uniformity in time," not the space uniformity or uniform heating of the charge (see page 2). Perfect "uniformity in time" is demonstrated by a straight and smooth line on the temperature-time chart. Such charts are frequently erroneously offered or taken as proof of uniformity in the load or in furnace space.

Moreover a temperature-time record, taken with the control thermocouple or thermometer, gives in most instances not even a true picture of temperature uniformity in time. The thermal inertia of the measuring device (thermocouple with protection tube) falsifies the picture of accuracy of temperature control. In fact by applying sufficiently heavy protection tubes it is possible in almost any furnace to obtain as straight a line as desired. It is therefore necessary to distinguish between true and apparent temperature curves, the apparent curve being drawn by the recording and control equipment of the furnace. The true curve is an ideal one, which could be obtained only by a measuring device without inertia and in intimate contact with the heating element.

The oscillation of the true temperature curve (difference between the maximum and minimum) depends on the following items: ratio of the instantaneous rate of energy input to rate of instantaneous energy consumption; thermal inertia of the measuring device of the control equipment (thickness of thermocouple protection tube, thermal properties of the latter); thermal properties of furnace wall and load; and characteristics of the control instrument.

In batch type operation, the ratio of rates of energy input and energy consumption changes with time (similar to the "excess ratio" e, page 41). The ratio is low for a cold furnace and cold charge and increases as furnace wall and charge become saturated with heat. The higher the ratio, the larger the oscillations become; the most extreme case is therefore the empty furnace at steady state (fully saturated with heat). Almost identical conditions exist at the end of the heating period when the charge is nearly at uniform temperature. However the greater mass (furnace walls + charge as compared with the walls alone for the empty furnace) has a fly-wheel effect, and therefore results in smaller oscillations. The oscillations found for empty furnace in steady state will not necessarily be noticeable during the heating-up period in the charge, or even on its surface. But with individual thin pieces placed in a relatively large furnace chamber, as for example tools heated individually, the oscillations act almost in full force on the charge.

Conditions have been analyzed in detail only for on-off control and empty furnace.[24] The sensitiveness of the control instrument is meas-

[24] V. Paschkis, *Mech. Eng.*, **67**, 445 (1945).

ured in degrees temperature and indicates the spread of the contacts which cause the heater to go "on" or "off." The sensitiveness influences the accuracy of on-off control.

It can be shown that the longer one control cycle lasts (time "on" + time "off") the wider the oscillations become. Thus the length of the cycle becomes an easy measure of the accuracy of control. For a given sensitiveness of the instrument and a given intermittency (time "on"/time "on" + "off") the length of the control cycle follows automatically. Thus as the furnace and charge starting from cold become saturated, the length of the control cycle increases. For example, Figure 45 shows the relationship between the true and the apparent temperature curve for one rather extreme case of a sensitiveness of 44 F and an intermittency of ⅛. Figure 46 shows true and apparent temperature differences, as well as sensitiveness, plotted against length of a control cycle. It is important to note that the setting of the control instrument must be different from the desired mean temperature. The control point settings are plotted as curve *d* in Figure 46.

(e) Location of Measuring Device

The position of the thermocouple in the furnace is of great importance because the accuracy of control depends on the location, which also influences the thermal uniformity of the charge. The modes of heat transfer from the heating elements to the load, the types of control (on-off, floating, etc.) influence the selection of the best location of the measuring device. When considering the relation of heat transfer and temperature control, a distinction should be made between furnaces with direct heat transfer (only thermal resistance, no mass, and subsequent lag between heating element and load, as for example in radiation type box furnaces) and those with indirect heat transfer (thermal resistance and mass between heat source and load, *e. g.*, externally heated lead baths). In direct heat transfer furnaces, operating with two-position control and fixed upper and lower values of the rate of energy flow, the thermocouple should be placed as near to the heat source (resistor) as possible. The load will gradually heat up and when it reaches the desired degree of uniformity should be taken out of the furnace or moved (in a continuous furnace) to the next station, unless it has to be held at temperature or cooled in the furnace.

If in such a furnace the thermocouple should be placed near the load, the temperature oscillations of the furnace wall and those of the surface of the load would become very much greater than those obtained with the thermocouple near the resistor.

Controls which gradually decrease the rate of energy input will operate satisfactorily if the thermocouple is placed near the surface of

the load. As the surface temperature increases, the rate of energy consumption decreases; little or no oscillation occurs.

Placing of an additional thermocouple in the center of the load is not only useless but frequently dangerous. The lag of the center temperature
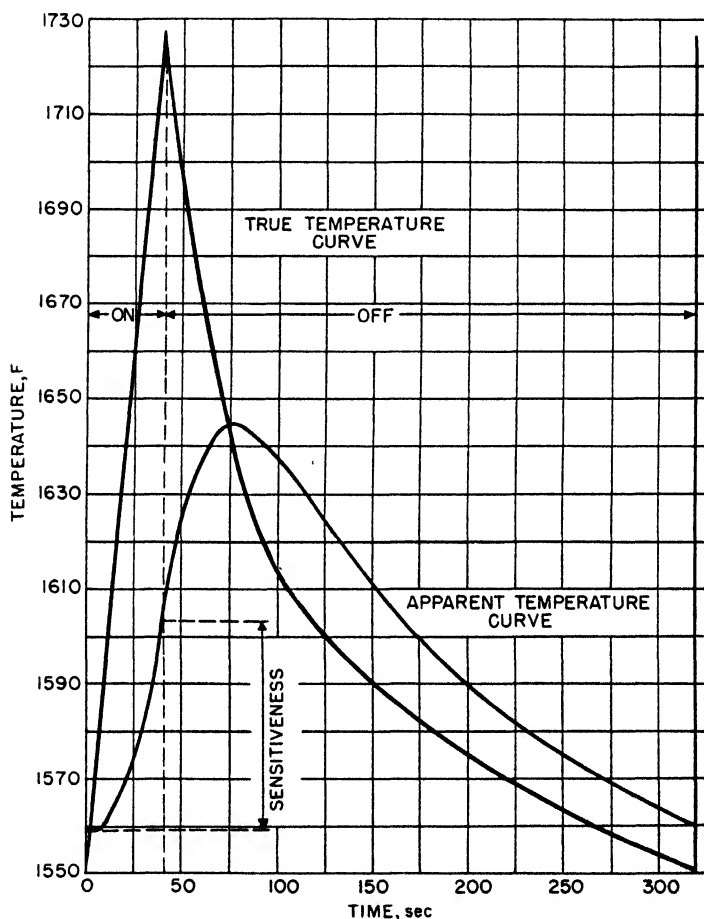
FIG. 45. True and apparent temperature curves (example). As the control instrument strikes the upper contact the heat goes off; when it strikes the lower contact the heat goes on. The spread of the contacts is called "sensitiveness of the instrument."

behind the surface temperature is unavoidable. The low center temperature will always require "more heat" and the surface is in danger of overheating. Using two thermocouples, one in the center and one on the surface, would establish only the total temperature gradient, which usually should not form the basis of heat supply to the surface. If
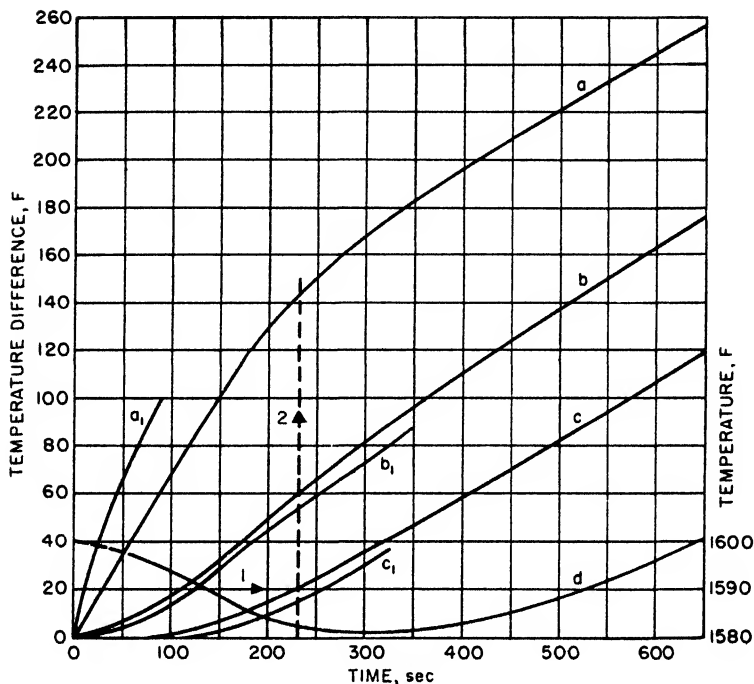
FIG. 46. True and apparent temperature differences as a function of length of control cycle.

a,	True temperature difference for weight of heater	0.38 lb/sq ft
a_1,	True temperature difference for weight of heater	0.19 lb/sq ft
b,	Apparent temperature difference* for k of protection tube	0.75 Btu/ft, hr, F
b_1,	Apparent temperature difference* for k of protection tube	0.375 Btu/ft, hr, F
c,	Sensitiveness for k of protection tube	0.75 Btu/ft, hr, F
c_1,	Sensitiveness for k of protection tube	0.375 Btu/ft, hr, F
d,	Control temperature for k of protection tube	0.75 Btu/ft, hr, F

* These curves hold for a weight of heater of 0.38 lb/sq ft.

In order to find the true temperature difference draw a line (example: arrow 1) from the ordinate scale to the curve of sensitiveness of the instrument; thence a perpendicular line (example: arrow 2) to the curve of true temperature difference.

feasible, two thermocouples, one at the surface, the other close underneath, could be used to control the rate of energy input on the basis of the rate of heat flow through the surface.

The control of furnaces with indirect heat transfer (resistance and mass between heat source and load) is much more complicated and in most cases cannot be satisfactorily solved with on-off control.

Consider, for example, an externally heated lead bath. The thermocouple operating an on-off control is located in the heating chamber surrounding

the crucible. The temperature there will be maintained within fairly narrow limits if the bath is in equilibrium (empty bath or constant throughout of rather small pieces which have a low weight compared with that of the lead). A certain temperature drop exists from the resistors and wall of the chamber to the outside of the pot, through the potwall and into the bath. If the throughput ceases suddenly, the heat stored in the lead between potwall and the point of immersion of the thermocouple will cause an increase in temperature in the thermocouple; the control instrument cuts off the energy input. Though the temperature of the heater will stop rising and (according to the amount of furnace insulation) even start to drop, it will still, for a considerable time, be higher than the temperature of the pot and lead. Consequently the temperature of the lead will continue to increase even long after the heat is shut off. Then first the temperature of the pot and finally also that of the lead will drop. The energy will be switched on again, but considerable time is required before the lead temperature can rise, since pot and wall must first be heated up again. A proper solution would consist in measuring the rate of heat flow through the potwall or within the pot and adjusting the input rate accordingly.

4. Conveying Mechanisms

The high cost of labor, the desire for quality and for elimination of error arising from the human element, and the trend of technology toward increasing replacement of physical labor by supervisory duties—all contribute to a continuously increasing use of automatic transport devices. Furnaces tend more and more to become heating machines. The almost infinite variety of types of conveying mechanisms makes a complete listing impossible. The apparently unlimited variety of devices can be arranged, however, in four main groups with occasional combinations. The groups are distinguished by their thermal relationship to the charge.

The first comprises conveying devices which never enter the furnace, and the second those which remain permanently in the furnace; the third includes devices which are brought into the furnace chamber for a short period only. Devices belonging to the fourth group remain in the furnace as long as the charge remains. Obviously the power consumption for the same kind of product will be different for furnaces with the different types of conveying mechanisms.

(a) Conveying Mechanisms Not Entering the Furnace

An outstanding example for this type is a pusher which transports part of the load or the entire load into the furnace by pushing on a dummy prepared on a rack outside the furnace. For convenience a piece of the load to be heated later can be used as dummy (Fig. 47). The pusher can be replaced by a chain operating outside the furnace and pushing the load into the chamber by fixtures attached to the chain.

In this group might be listed continuous strip and wire furnaces; the coiling device located outside the furnace pulls the load through the
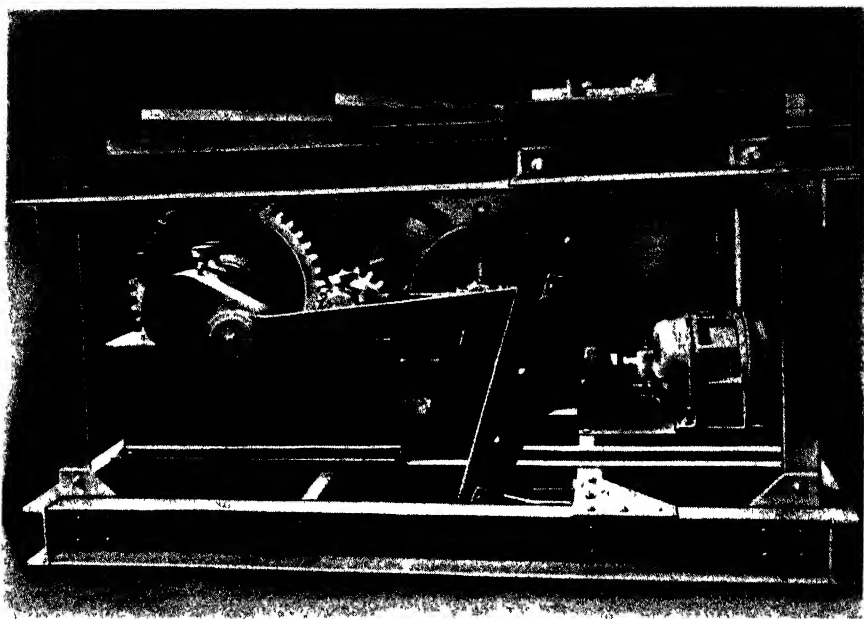
FIG. 47. Pusher type conveying mechanism. (Courtesy *W. S. Rockwell Company.*)

furnace. If the load is in itself not stiff enough, a heavier supporting strip can be pulled through together with the material to be heated. Thus, however, some advantages of this type of conveying mechanism must be sacrificed because the dead weight of the supporting strip is being introduced.

All loading devices used in electrode salt bath furnaces belong in part or entirely to this group. Either overhead chains, from which the load is suspended, may be used, or on either side of the furnace a rail can be placed on which a sort of carriage is moving. The load hangs from the carriage into the bath. If the load consists of small pieces it is of course placed in baskets; otherwise it may be held directly. In some cases (hollow bodies, light metals), the buoyancy of the charge in the bath makes it necessary to fix the position of the charge in order to prevent rising of the load out of the salt or lead. Figure 48 shows two arrangements used in connection with salt baths.

(b) *Conveying Mechanisms Continuously in the Furnace*

WALKING BEAMS

The principle of this conveying mechanism is shown in Figure 49.

The hearth, *A*, of the furnace has two or more slots, *B*, in which the walking beams, *C*, move. The walking beams are activated, for example, by

eccentrics, causing each point of the beam to move in a prescribed manner, following a circle or an ellipse or possibly a rectangle. Through this movement the charge, D, is lifted off the furnace hearth, is moved on for a distance, x, and is then deposited again on the hearth. The transport mechanism can be located in or below the slots; if the walking beams extend through the doors then the moving mechanism can be located outside the furnace. Lines 1 through 4 indicate different positions of the top of the walking beams.
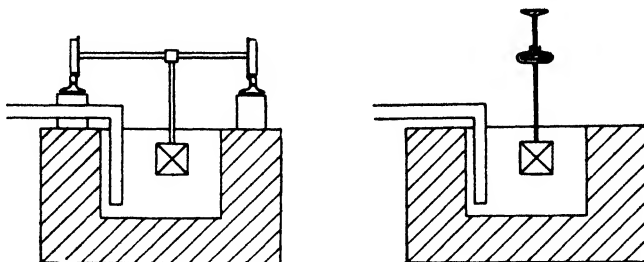
FIG. 48. Conveying mechanism for salt bath.
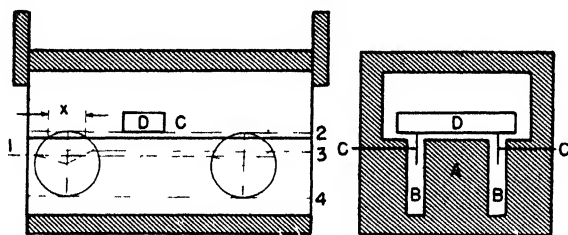
FIG. 49. Principle of the walking beam.

If the furnace temperature is so high as to preclude this design because the bending stresses in the load would become excessive, a modified arrangement can be selected. Parts of the hearth are detached and built on walking beams, perhaps as in Figure 50. It is possible to assemble the entire walking beam arrangement on a carriage so that the complete beam can be withdrawn from the furnace for repair and inspection. Heaters are sometimes provided in the beam or in the slot facing the beam to compensate for the heat loss through the slot and thus improve temperature uniformity.
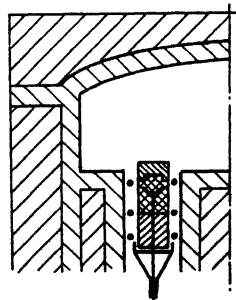
FIG. 50. Walking beam—design for high temperatures.

ROLLER-HEARTH FURNACES

The hearth of the furnace is covered by a number of rolls which carry the load. Depending on size and weight of the individual pieces of the load, the rolls are spaced more or less closely.

The individual rolls are mostly made of heat-resisting alloys, sometimes water-cooled. The rolls are carried in bearings which are generally outside the furnace wall (see Fig. 110, page 138). The many breaks in the sidewalls (two for each roll) cause considerable heat loss. Frequently the rolls are driven by chains on the outside Figure 51 shows a roller-
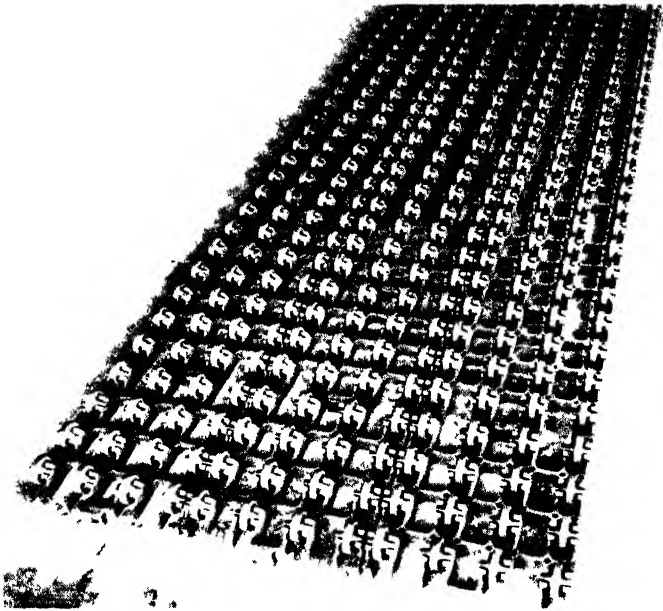

FIG. 51 Roller-hearth arrangement. (Courtesy
Michiana Products Corporation.)

hearth arrangement where the rolls do not extend through the sidewalls. Nonmetallic rolls, as of silicon carbide, have been proposed but are not used widely.

ROTARY-HEARTH FURNACES

The furnace hearth (Fig. 52) has the shape of either a disk or a circular ring and rotates in the furnace chamber. The latter may have one or two doors for charging. If two doors are used, a baffle for the separation of ingoing and outgoing load is frequently put between the doors, thus preventing a cooling of the outgoing load by the cold ingoing material. Guard plates prevent the dropping of pieces off the hearth. Sand seals are sometimes used to prevent infiltration of cold air into the chamber.

A drum (Fig. 111, page 139) of heat-resisting alloy rotates slowly around an inclined axis. The drum is heated from the outside. Usually such furnaces are charged through a hopper, although, when the charge consists of small pieces, a spoon-like device may be used, from which the pieces are dropped into the drum. Steady flow of the charge through the drum is maintained by a spiral thread forming an integral part of the inside drum wall.
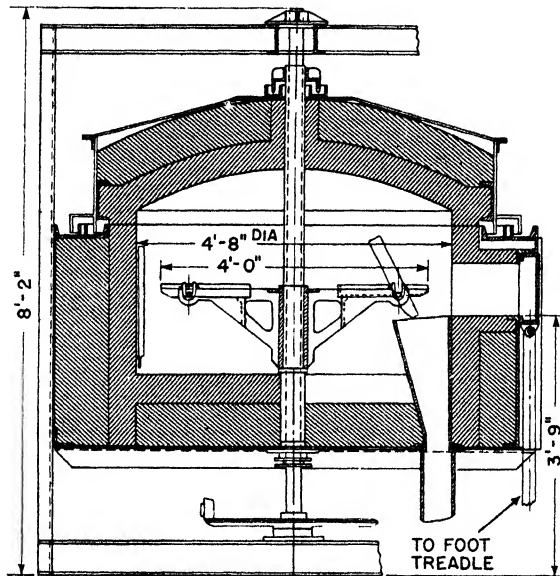
FIG. 52. Rotary-hearth furnace. (Courtesy *The Electric Furnace Company.*)

CONVEYOR BELT CONTINUOUSLY IN THE FURNACE

If a conveyor is so arranged that it extends out of the furnace chamber, it inevitably loses part of the heat stored in it. However, an arrangement as shown schematically in Figure 53 avoids this disadvantage.
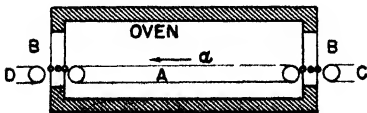
FIG. 53. Special design of conveyor belt.

The conveyor, A, moves the charge in direction of arrow α through the furnace. Delivery of the charge is made by conveyor C and the take-off by conveyor D. Transport from C to A and from A to D is accomplished by means of mechanism B. B may consist, for example, of a number of separately driven rolls. Conveyor A never leaves the furnace and thus the heat stored in A is not lost.

Instead of the individually driven rolls (*B*, Fig. 53) the feeder conveyor and the furnace conveyor can have sprockets on the same shaft.

COMPARISON OF ARRANGEMENTS OF THIS GROUP

Walking beams have advantages both at low and at high temperatures; they are very desirable for low temperatures, for which their design becomes quite simple. I beams can frequently be used, and the heat loss by conduction in the beams is not too great. For high temperatures walking beams are desirable, because the mechanically sensitive parts of the conveying mechanism are protected against heat. The main disadvantage of walking beam furnaces is the repeated speeding-up and slowing-down of the charge, resulting in a relative movement between beam and charge and consequently in a danger of surface scratches on the charge. Walking beam furnaces can readily be used for semicontinuous work, loading the furnace by a few quick steps, then standing still, and moving again for discharge.

Conveyors eliminate the danger of relative movement between charge and conveyor and of scratches. However, intermittent operation is mostly out of the question, because of the danger of local elongation of the conveyor under the influence of heat.

Rotary-hearth furnaces are very economical in power consumption. The same person can often load and unload, since the charging and discharging doors are close together. But they do not provide for transportation of the load in the shop outside the furnace, as conveyor furnaces can be made to do.

Rotary-drum furnaces are limited to not too bulky pieces which will not be injured when moving in the drum.

Roller-hearth furnaces cause considerable heat loss because of the great amount of through metal. Only rarely are they built for electric heating.

(c) *Loading Devices Remaining in Furnace for Short Time Only*

CHARGING MACHINE WITH SUPPORTING ARMS

If the charge is sufficiently sturdy to permit a noncontinuous support during heating, the furnace bottom can be shaped as shown in Figure 54. This manner of charging is used in furnaces for heating piles of sheets, or strip and wire coils in batch type operation. In another device the charging machine has tongue type arms gripping the charge on the side (Fig. 55).

CHARGING MACHINE WITH LIFTING PLATFORM

Supporting arms cause difficulties because of distortion unless the arms are made excessively heavy. The same result as with supporting
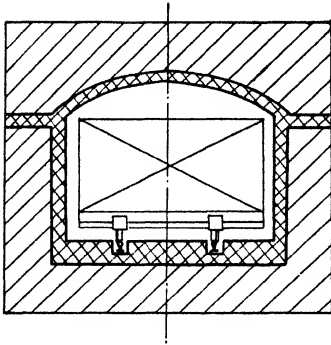
FIG. 54. Charging machine for slotted bottom. The furnace must be high enough to permit lifting of charge for its withdrawal.
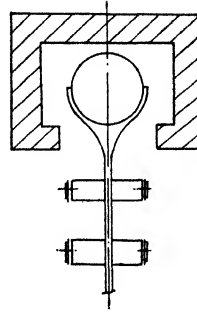
FIG. 55. Tongue type loading machine. The furnace must be wide enough to permit withdrawal of prongs after depositing of charging machine.

arms can be achieved by a charging machine having two platforms, the lower one connected to a carriage moving in the slots, the other rolling on inclines of the lower platform. Figure 56 illustrates such a machine.

COMPARISON OF ARRANGEMENTS OF THIS GROUP

In all designs shown above, space is lost and therewith the heat loss increases, because of the charging machine. The device shown in Figures 54 and 56 requires extra height of the furnace and that in Figure 55, extra width. The latter, moreover, puts considerable stress on the charge and can therefore be used only for material which can stand some rough handling. The device in Figure 54 is much simpler than the one in Figure 56; but the first is limited to furnaces of moderate length, perhaps 6 to 10 ft, depending upon temperature and weight of the charge.

FIG. 56. Charging machine with lifting platform. Wheels A move in slots of the furnace hearth or on rails below the furnace. Shaft B is turned by means of cranks and thus platform C is lowered to the level of the carriage D by means of rolls. The charge is deposited on bridges in the furnace.

(d) *Loading Devices Remaining in Furnace as Long as Charge*

CONVEYORS [25]

Conveyors of various design should be mentioned, *e. g.*, mesh belts, trays connected together to form a continuous belt, and heat-resisting sheets welded together to form a continuous loop.
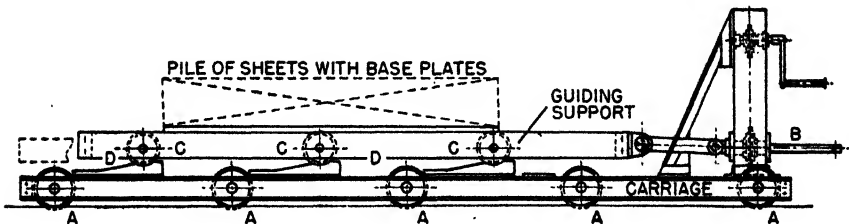
Conveyors are subject to pull and must be strong enough to withstand the stresses at the operating temperature of the furnace. For low temperatures and short furnaces the chain can run unsupported and be permitted to sag under the weight of the charge; but in most cases the furnace temperature is too high for such a procedure. Then the chain or conveyor slides on continuous supports or over supporting rolls, spaced
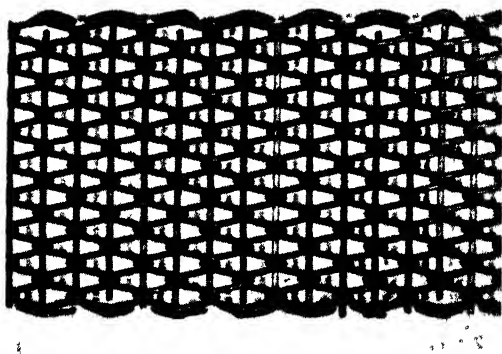
FIG. 57. Mesh conveyor (Courtesy *Wickwire Spencer Steel Company*)

regularly over the furnace length, and additional wear due to friction occurs. Figure 57 shows an example of a mesh conveyor. The maximum weight which such a conveyor can carry depends among other factors on the temperature, the carrying length, and the distance of the point of maximum temperature from the pulley. A load of 10 to 16 lb per sq ft at a furnace temperature of 1700 F and a load of 6 to 7 lb per sq ft at 2100 F are typical examples. 2100 F is approximately the maximum temperature for mesh conveyors.

For heavy loads cast conveyors are used (Fig. 58). Sometimes cast trays connected together by links are used as conveyors. The maximum temperature for cast conveyors is approximately 2000 F.

Conveyors of any of the designs mentioned above are subject to temporary elongation while exposed to the high furnace temperatures and to permanent elongation due to creep. Therefore, on one side the bearings must be adjustable so that the shaft can follow the elongation. The adjustment is made automatically either by weights or by springs, thus keeping the conveyor always stretched.[25]

[25] W. F. Ross, *Heat Treating and Forging*, 26, 457, 507 (1940).

CAR BOTTOM FURNACE

Next to conveyors cars put into the furnace are the most common type of loading device of this group. For low-temperature oven work the car can move on tracks inside the furnace. For higher temperatures the entire bottom with refractory lining is put on the carriage and removed with the load from the furnace: this design is called car bottom furnace (Fig. 59). In order to prevent infiltration of cold air, a sand or similar seal must be used.
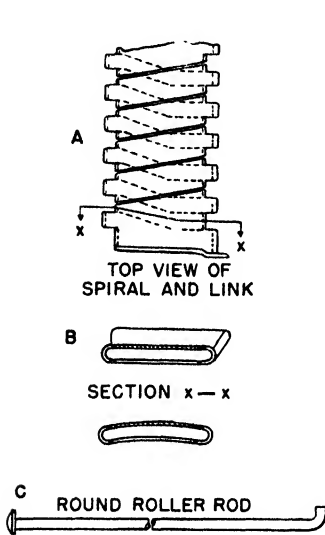
FIG. 58. Cast conveyor. (Courtesy *General Alloys Co.*)
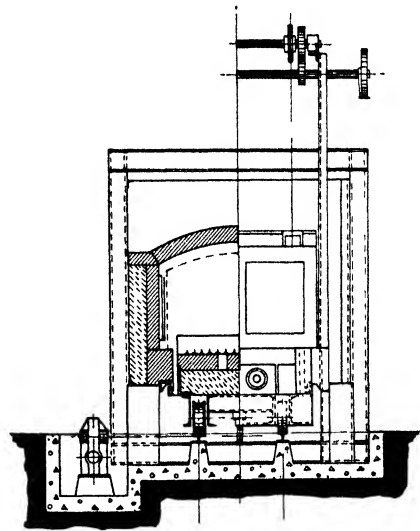
FIG. 59. Car bottom furnace. (Courtesy *Electric Furnace Company.*)

Car bottom furnaces should be used primarily for charges with heavy sections and for bulky charges. Loading is easy, because it is done outside the furnace, but the heat economy is poor because of the heat stored in the car lining; and for heating of masses of small parts the uniformity of heating is obviously very poor.

OVERHEAD TROLLEYS

Sometimes overhead trolleys on which racks are moved through the furnace are used in ovens. This design is not employed at high temperatures.

(e) Combined Arrangements

The grouping given above cannot be maintained rigidly. A number of combinations of the various types of conveying mechanisms are in use.

Figure 60 illustrates a trolley outside the furnace, with racks suspended on hangers; the hangers move in a slot in the roof, and the two halves of the roof must therefore be suspended separately.
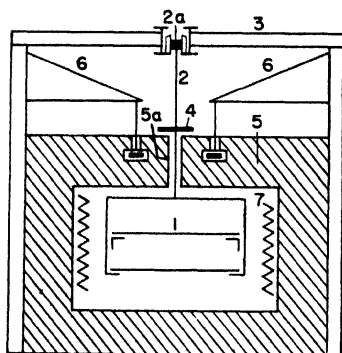
FIG. 60. Trolley type conveyor. (1) Shelves for the charge. (2) Suspensions for shelves connected to small carriages (2a) which run on rails. Rails are held by frame (3). The suspensions (2) are equipped with seals (4) and thus prevent leakage through the slot (5a) in the furnace cover (5). Cover (5) is held by supports (6). (7) Furnace walls. The trays (1) are just as long in the furnace as the charge and therefore represent dead weight, but suspensions (2) and carriages (2a) do not influence heat consumption. Suspensions should be made at least partly of material with low thermal conductivity.

B. Parts for Radiation Furnaces

1. Resistors

Resistors, the most important individual item in the design of resistor furnaces, are the element of highest temperature and therefore most exposed to the possible danger of failure. Proper design and selection of resistor material determine the length of life which may be expected from a resistor.

(a) Material for Metallic Resistors

The factors limiting the use of materials as resistors are chemical and physical strength rather than melting point. To take only a trite example, steel has a melting point of some 2600 to 2700 F, and yet it is obvious that it cannot be used for resistors in furnaces with operating temperatures even as low as 1000 F. The steel would oxidize much too quickly, and even if operated in protective atmosphere, the lack of sufficient creep strength and the danger of warpage would exclude its use at temperatures above 1300 F.

For resistor temperatures up to 2100 F, or exceptionally 2200 F, alloys of nickel and chromium are generally used. For both oxidizing and reducing atmospheres the generally accepted composition of the resistor material is 80% nickel, 20% chromium; however, for heater temperatures below approximately 1800 F, other less expensive alloys are sometimes used as follows: alloys of nickel, chromium, and iron are applied in various compositions, containing roughly between 25 and 50% iron and 15 to 20% chromium, the lower chromium and higher iron content usually concurring. These alloys, depending upon their iron content, are employed when resistor temperatures do not exceed 1600 F (iron content 50%) to 1700 F (iron content 25%).

For low temperatures up to approximately 1000 F, copper–nickel alloys are sometimes used. In rare cases nickel, nickel–manganese, or nickel–iron resistors are used for temperatures up to approximately 1200 F. They are desirable for certain types of small furnaces and for appliances because of their very steep temperature gradient, resulting in a form of autoregulation in case of nonconstant voltage. With increasing voltage, the resistance of this type of metal also rises, and the input decreases automatically, thus counteracting overheating. Conversely if the resistor is cooled excessively (e. g., by introduction of a new charge) the resistance drops and the input increases temporarily.

In recent years a new type of alloy for resistors has been developed, consisting of chromium, aluminum, and iron, and sometimes cobalt. This type of material seems to withstand oxidation very well,[26] even at high temperatures of approximately 2460 F. But it is claimed to have some mechanically undesirable features, being brittle at room temperatures and becoming more so on repeated heating and cooling. Moreover, the material shows definitely appreciable growth in protracted use (in the order of magnitude of 0.25 in. per ft) and must be formed at a dull red heat. It is because of the mechanical difficulties of this type of resistor material that it has not replaced nickel–chromium at temperatures at which the latter is safe.

Some of the properties of resistor materials are listed in Table VIII.

TABLE VIII

PROPERTIES OF METALS FOR RESISTORS

Composition (approximate)				Resistivity at degrees F						Density lb/cu in.	Coeff. of expansion $\times 10^{-6}$ per degree F and code for Remarks
Cr	Ni	Fe	Others (%)	70	500	1000	1500	2000	2400		
20	80	—	---	650	680	695	690	700	—	0.304	17[a]
16	60	24	—	675	713	742	759	—	—	0.298	17[a]
—	45	—	Cu (55)	294	295	299	—	—	—	0.320	[b]
—	70	30	—	120	288	374	—	—	—	0.305	[c]
37.5	—	55	Al (7.5)	1000	—	—	—	—	1040	0.249	18[d]

Remarks: [a] Temperature range 70–1832 F. Data from Driver-Harris Company, Hoskins Manufacturing Company, and Wilbur B. Driver Company. [b] Temperature range 70–212 F. Data from Hoskins Manufacturing Co. [c] Data from Wilbur B. Driver Company. [d] Temperature range 70–2400 F. Data from A. O. Smith Corporation contained in the first article of reference 26 below.

[26] S. L. Hoyt and M. A. Scheil, *Trans. Am. Soc. Metals*, 23, 1022 (1935); W. Hessenbruch, *Elektrowärme*, 7, 7 (1937); W. Fischer, *ibid.*, 7, 255 (1937); A. Grunert, W. Hessenbruch, and K. Schichtel, *ibid.*, 5, 2 (1935); G. Nordstroem, *Jernkontorets Ann.*, 88, 572 (1933); G. Nordstroem, *Elektrowärme*, 5, 79 (1935); A. Grunert, W. Hessenbruch, and K. Ruf, in *Die Heraeus-Vacuumschmelze*, Alberti, Hanau am Main, 1933, p. 169.

The figures vary with slight variation in composition among the products of different manufacturers.

Cast resistors also are used. The properties of cast material are of course somewhat different from those of rolled material.

Frequently the problem of life expectancy of heater units is considered related to composition. Within limits this of course holds true, but life expectancy is considerably better for heavy sections than for thin ones. This may be understood from the fact that any irregularity of, for instance, one or two thousandth of an inch, almost unavoidable in manufacture, constitutes a much larger percentage of the total cross section in a small wire than in large ones.

The life expectancy increases rapidly with lowered temperature. The A.S.T.M. tests [27] exaggerate conditions of actual operation by subjecting very fine wires to intermittent heating at extremely high temperatures. Thus a reproducible test can be carried out in reasonably short times (1000 hr). Since it is difficult to apply the results thus obtained to the life of wires and ribbons as used in industrial heating practice, none of these curves is presented here. Suffice it to say that apparently the logarithm of life increases in inverse proportion to the wire temperature.

(b) Design of Metallic Resistors

RIBBON TYPE RESISTORS

These are either arranged in loops on the sidewall or suspended from hooks, particularly for roof heating (see Figure 97 for example of one type of heater) or sometimes in frames (for top or bottom) which in case of failure allow exchange without shutting down of the furnace (Fig. 61). In designing, special care should be taken to avoid all "heat shades" or muffling of the resistors: local overheating and subsequent early destruction of the resistor would result.

Figure 62 shows a well designed suspension brick: contact between ribbon and brick is limited, and the danger of local overheating of the resistor is avoided. Various means have been suggested to overcome the danger of overheating at the point or line of contact: reinforcement of the ribbon, and metal edges on the carrying surface are two examples. If the ribbons are very thin, as below $\frac{1}{16}$ or $\frac{1}{32}$ in., and if the temperatures are high, there is the danger of warpage. This danger can be sometimes lessened by taking heavier stock than necessary from a purely thermal viewpoint.

Although a large cross section of the ribbon reduces the danger of warpage it does not influence the creep strength of the arrangement on
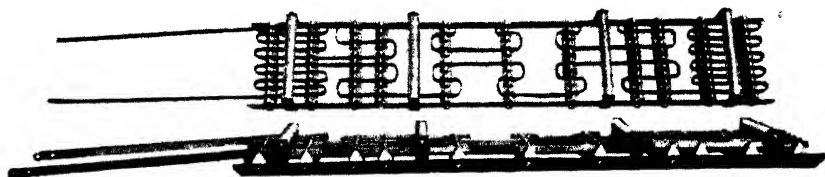
[27] ASTM Method B76–39.

Fig. 61.   Ribbon type resistors.   (Courtesy *General Electric Company*.)

vertical walls.   Each loop of the resistor must carry its own weight. Increase of cross section does not help because both weight and strength increase in proportion to the cross section.   If with a given design the creep strength is not sufficient, the length of each loop must be decreased, possibly by arranging two or more groups of ribbons one above the other on each vertical wall.

Heavy electric loads offer another limitation to this type of resistor.   These may result in serious ribbon temperature differences, which can lead either to warpage or to premature destruction. These differences, it should be noted, are due to mutual radiation of neighboring ribbons and nonuniform heat dissipation, not to any muffling effect; heat is withdrawn more quickly in the parts of the ribbon close to the charge than in those farther away.
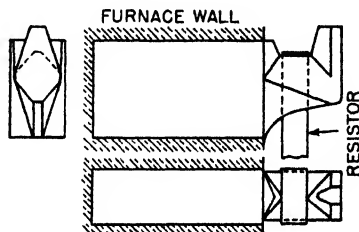

Fig. 62.   Suspension brick for side wall heaters.

By way of example, some unpublished experiments are cited.[28]   Figure 63 shows schematically two ribbons in plane view, each divided into four sections and touching the furnace wall with one small side and the charge with the other.   The charge is considered to be at a constant temperature of 1832 F (1000 C).   The arrows in the figure show all possible lines of heat exchange. Arrows marked *1, 2, 3, 4,* and *5* refer to radiation, paths *6, 7,* and *8* to conduction; the letters beside the arrow number refer to the sections of the ribbons. By electric experiments described in the above reference, various combinations of conditions were analyzed; the results can be summarized as follows:

(1)   With increasing energy density the temperature difference increases almost proportionally.   For a particular case temperature differences of approximately 20 F occur, even at the moderate load of 4.5 kw per sq ft inside

---

[28] The experiments described above were carried out by J. Gadiot under the direction of the author in the laboratories of the Stroomverkoop Mij, Maastricht, Netherlands.   The results are published here for the first time.   See also *Elektrotech. u. Maschinenbau,* **54,** 617 (1936); and Volume I, p. 27.

wall area. The conditions in this case were: spacing of the ribbon 1.2 in. (30 mm), ribbon 1.2 in. × 0.12 in. (30 mm × 3 mm); charge temperature 1832 F (1000 C). Thermal conductivity of the ribbon 11.7 Btu per ft, hr, F.
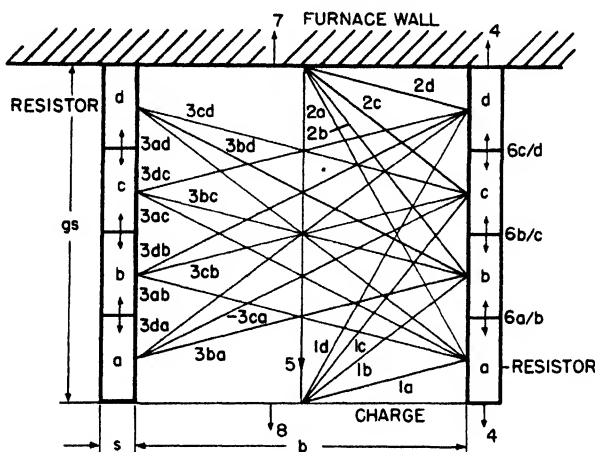

FIG. 63.   Heat exchange between two ribbons.

(2) The thermal conductivity of the ribbon does not contribute very much to heat equalization: in the ribbon described above, and with an energy density of 8.9 kw per sq ft the values given in Table IX have been found.

TABLE IX

TEMPERATURE DIFFERENCES AND THERMAL CONDUCTIVITY

Thermal conductivities of ribbon, Btu per ft, hr, F	Maximum temperature difference, F	
	In ribbon	Ribbon to charge
0	99	385
5.85	68	373
11.7	56	368

(3) The heat loss from the wall has but a very small influence on the temperature distribution in the ribbon.

(4) The geometry of the ribbon has considerable influence. Calculations based only on the specific energy density are misleading and should be used with great care and only with corrections (see page 85 and Fig. 72). As example four cases described in Table X were tested.

For a temperature of the load of 1000 C (1832 F) and an energy density of 95 kw per sq m (8.83 kw per sq ft) the four designs compare as shown in Table XI.

TABLE X

DESCRIPTION OF HEATER DESIGN

Design	Width of ribbon		Spacing between two ribbons		Thickness of ribbon	
	mm	in	mm	in	mm	in.
A	30	1.18	30	1.18	3	0.118
B	20	0.79	20	0.79	2	0.079
C	80	3.15	20	0.79	2	0.079
D	20	0.79	80	3.15	2	0.079

TABLE XI

HEATER PERFORMANCE DATA

Design	Ribbon temperature		Temperature difference, F	Furnace wall temperature, F	Energy density, W/sq in	Material used, lb/sq ft wall area
	Max., F	Min, F				
A	2197	2145	52	2064	30.7	4.70
B	2192	2147	45	2066	30.7	3.16
C	2241	2093	148	2090	7.6	12.68
D	2449	2408	41	2012	122.8	0.849

The load of 8.83 kw per sq ft is obviously excessive. But the results are interesting, showing the superiority of design B over design A. Both have the same energy density, but design B requires 30% less material than design A.

Design D is interesting because compared with the savings in material (approximately 75% of the material, design B, is saved) the increase in ribbon temperature is modest. Design D was investigated as a limiting case; not only the temperature of 2450 F, but also spotty radiation to the load because of the extremely wide spacing, would exclude its actual use.

The geometry of ribbons has been studied in detail by Fischer.[29] Assuming uniform temperature throughout the ribbon, he determined the influence of thickness and spacing on the temperature of the ribbon as related to the used weight.

Figure 64 shows a ribbon type resistor developed in Germany, in which profile-rolled ribbons are placed parallel to the wall. The given contour results in good mechanical strength, the slight thickness perpendicular to the wall producing almost perfect temperature uniformity in the resistor. Consequently this type of resistor can be operated at higher temperatures than common ribbon type resistors, which means either

[29] W. Fischer, "Radiation of Open Heating Elements," First International Congress for Electrothermics and Electrochemistry, Scheveningen, Netherlands, 1936.

increased range of furnace temperatures or higher permissible specific
load.   The disadvantages of the design lie in the necessity of many welded
connections in the furnace and in a low resistance of the resistor per unit
of wall area.   Consequently many furnaces equipped with this type of
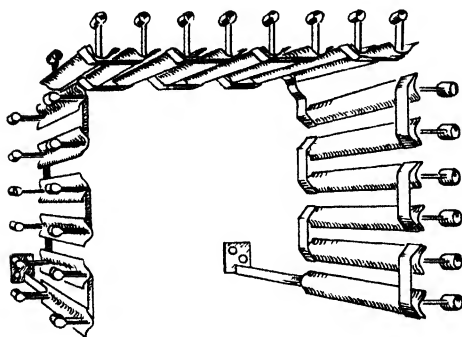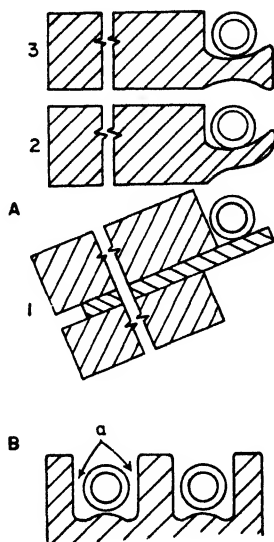resistor need transformers.

FIG. 64.   Rim type resistor.

FIG. 65.   Brick arrange-
ments for resistor coils: A,
sidewall; B, bottom.   ⟶

RESISTOR COILS

Round resistor wires are chiefly used in the form of coils with or
without core.   Coils without core are placed in recesses in the furnace
wall.   Figure 65A shows three different ways of providing for such re-
cesses.   Inevitably dirt and dust accumulate in the bottom of the grooves,
particularly in bottom heating elements.   If not properly cleaned the
dust covers part of the coils, causing local overheating and shorter life.
This danger is decreased by the design shown in Figure 65B; dust may
accumulate in the corners (a) and need to be removed only at prolonged
intervals.   Since coil and refractory have contact only along a line there
is but little chance of the resistor being covered before all the spaces a
are filled.

In resistor coils with core the mechanical stress of the wire is greatly
reduced; each turn is supported individually.   Consequently thinner
wire, which, as discussed above, results in smaller weight for the same
temperature of the wire and the same energy density, can be used. ·

Figure 66 shows a resistor coil with core.   The left half shows a wire
wound around the core in the form of a helix.   In the right half a helical

coil of thin wire is wound around the core in form of another helix. In this latter design the mechanical strength inherent in the core permits a low weight of the wire by use of many parallel circuits and small diameter wire.
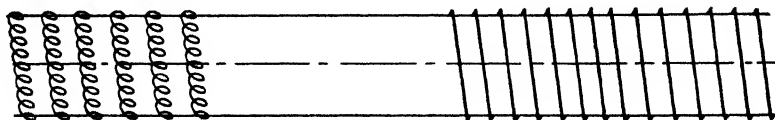

FIG. 66.   Core type resistor coil.

Resistor coils with cores can be arranged so that they can be replaced without shutting down the furnace. For this purpose the return lead can be placed in the hollow of the supporting tube and may even possibly extend on one side so as to rest in the furnace wall. In other instances it has been proposed to keep the hollow of the supporting tube clear, so that a metal rod can be inserted only when and if the resistor must be withdrawn from the furnace.

EMBEDDED RESISTORS

For temperatures up to approximately 1700 F, embedded resistors have found a useful place. Figure 67 shows such an embedded resistor. A number of wire coils are placed in refractory cement so as to form a solid plate or hollow cylinder. The advantages of this type of heater are obvious: it is less subject to accidental injury by careless handling, and it gives a more uniform temperature. Moreover, it permits simple wall design, particularly for round furnaces (see page 134). Their disadvantages are: limitation in maximum temperature since the wire has to reach a higher temperature than if exposed in

FIG. 67.   Embedded resistor.

order to force the heat through the refractory material, and less accurate temperature control. It is impractical to measure the temperature of the wire proper, and consequently the temperature oscillations in controlling by on-off control are larger than with open resistor elements.
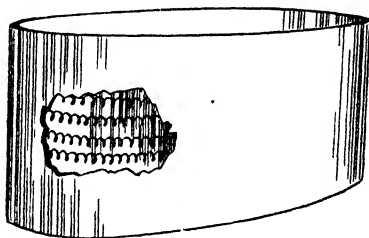
FRAME RESISTORS

Frame resistors are used for low temperatures, up to 1000 or 1200 F. They come readily assembled and are easily attached to the furnace walls, particularly where a metal structure is available for mounting

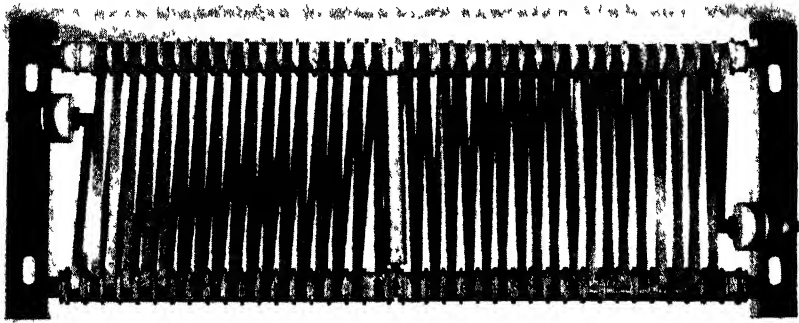them (Fig. 68). Each frame is a self-contained unit, usually having a connected load of from 1 to 5 kw.

FIG. 68.   Frame type resistor.   (Courtesy *Westinghouse Electric and Manufacturing Company*)

Insulators (Fig. 69) are slipped over metallic rods, which are connected at the ends by cross pieces and thus form a rigid frame.   Over the insulators, strip, or more rarely wire is wound in continuous length.
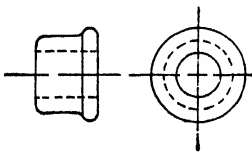

FIG 69.   Insulator for frame type resistor.

Except in furnaces with forced circulation, the two layers of the resistor do not heat uniformly; this is one reason for the limited temperature for which this type of resistor can be used.   On the other hand a substantial connected load can be applied to a limited space, so that the units are desirable where excess temperatures of the heater are not objectionable.

OTHER DESIGNS

The desire for unusually sturdy resistors with heavy cross section has led to the use of cast resistors.   Their mechanical strength constitutes their main advantage.   Their greatest disadvantage is the low voltage (inherent in the design) which necessitates transformers, particularly in small furnaces.   Another disadvantage lies in the inevitable irregularities in a cast structure.   A local narrowing results in a higher resistance, producing higher temperatures and possibly subsequent premature failure.   However this danger is less than might appear at first, because any local overheat is carried away relatively easily by thermal conduction through the heavy cross section.

The electric load of resistors is limited by the maximum permissible temperature which the resistors may reach.   The better the resistors are

"cooled" by neighboring walls or the charge, the higher is the energy which may be impressed on them. In most cases resistors dissipate their heat by radiation or convection. An attempt has been made to utilize both by means of tubular resistors. The furnace atmosphere moves in free or forced movement through the tubes while the outside radiates.

Molybdenum has a very high melting point and a fairly good mechanical strength at elevated temperatures. Unfortunately it oxidizes very rapidly in air. Designs with molybdenum coils, in gas-tight ceramic tubes filled with protective gas, have been tried but have not reached the practical stage. If they should be fully developed for practical use, they promise high-temperature metallic resistors with high permissible load density.

INFRARED LAMPS

For low temperatures, heating by infrared lamps has been in use in recent years. As heat source, incandescent lamps—with metallic or carbon filaments—are frequently used. Inasmuch as the lamps are of standard design they will not be discussed in this section (see page 125).

RESISTOR TERMINALS FOR METALLIC RESISTORS

In the heating chamber of a furnace, the body of the resistor can easily transfer its heat to the adjacent charge. But also in the connectors which connect the resistor with the power supply outside the furnace, heat is generated, and this heat cannot be distributed so easily, because the connector is surrounded by insulating material. The heat generated within can be transferred to the surroundings only by an increase of the temperature of the connector above that of the surrounding insulation. To avoid excessive temperatures in the connector, the cross section of the connectors is increased considerably as compared with that of the resistor element proper. But increasing the cross section of the connector decreases the resistance to heat flow and increases the heat loss by conduction through the terminal.

An optimum cross section, through which the total losses—electric plus thermal—become a minimum, should be sought. The problem has been discussed in Volume I (page 57) and an approximate solution is given. No accurate solution is yet available.

The cross section of the terminal is customarily made from two to four times that of the resistor proper. Connections between resistors and terminals are butt- or arc-welded. In some instances the wire or ribbon is covered by a tightly wound coil of several layers of thin wire of either the same or a better conducting material than the resistor. In

many cases the terminals of the resistors do not rest directly in the wall material but are contained in a tube of refractory material.

INSULATORS FOR RESISTORS

Frequently it is not desirable or feasible to rest the resistors directly on the refractory or insulating refractory material forming the inside furnace wall. One factor against direct contact is possible chemical reaction in view of dirt or slag deposit and/or special furnace atmosphere. Another reason may be the necessary intricate shapes or the small cross sections of the insulating material.

Special insulators, then, are made to meet these specifications. High electric resistivity and resistance to thermal shock are the main requirements. The most frequently used material for such insulators is alundum (aluminum oxide) and materials of the steatite class. Carbon deposits on brick are sometimes very heavy, and therefore glazed insulators which are less susceptible to absorption of deposits are used.

(c) Design of Nonmetallic Resistors

Nonmetallic materials used as resistors comprise carbon (and graphite) and silicon carbide. Carbon resistors are very seldom used; in oxidizing atmosphere they burn off at a considerable rate. An interesting development, using granular carbon in refractory tubes filled with protective atmosphere,[30] has not yet resulted in a commercially applicable design. An example of a steel melting furnace with graphite resistors is given on page 151. Properties of carbon and graphite are discussed in Volume I, page 124.

The most important type of nonmetallic resistors is made of silicon carbide, the best known of the type in the United States being Globar.

Silicon carbide resistors have a number of peculiar characteristics, distinct from any metallic resistor. First their change in resistivity with temperature is considerable and irregular. Starting from cold, the resistivity drops by about one-third, reaches a minimum at approximately 800 F, and then increases; hollow units, which are used when the outside diameter becomes larger than one inch, drop in resistivity again at 2400 F and start increasing in resistivity again at 2500 F.

In addition to the change of resistivity with temperature, there is an increase of resistivity with time in the order of magnitude of 1 : 5 or more. In order to maintain approximately the same connected load during the entire life of such a resistor, a variable voltage has to be applied, usually by step transformers. These transformers have a total voltage range

[30] M. G. Toole and R. E. Gould, *Trans. Electrochem. Soc.*, **70**, 89 (1936).

from below the rated voltage of the resistors (perhaps from 0.7 of the rated voltage) up to two or three times the rated voltage. By initially applying low-voltage, furnaces tend to heat up slowly, with resulting increased resistor life.

To obtain sufficiently smooth change of voltage a large number of transformer steps are required. The Carborundum Company, producer of Globar, recommends as many as 36. Through special design the number of taps on the transformer need be only eleven for this purpose. On one end of the winding there are five steps, each equaling $\frac{1}{35}$ of the total voltage range (difference between maximum and minimum voltage). On the other end of the winding there are five steps, each equaling $\frac{2}{35}$ of the total voltage range. By alternately selecting taps on either end of the winding, steps equaling $\frac{1}{35}$ of the voltage range can be had over the entire voltage range.

The increase of resistivity with time is not regular and is different for individual units. In some cases the resistivity grows quickly during the first 100 or 200 hours of service and then remains nearly constant; in other cases the increase is fairly steady over the entire lifetime.

Life expectancy figures for such resistors are difficult to give. Life depends on a large number of circumstances, some of which are listed here: furnace temperature, surface load, furnace atmosphere, type of operation (continuous or intermittent, exposure of elements to cold air when the furnace is opened, etc), type of temperature control, and finally range of the transformer which changes the voltage for the units—a large voltage range allows utilization of the resistors even if their resistivity has increased considerably.

In view of these many variables, the following figures can be only indicative with a very wide allowance. In rare cases where the temperature was controlled by a reactor without much change during operation, a life of more than 8000 hr was observed with a furnace temperature of 2460 F during operation and of 1800 F during nights, week-ends, and holidays. On the other hand, in poorly designed furnaces and under the influence of vibration, resistor life as short as 100 hr has been experienced.

At temperatures of approximately 2500 F a life of from between 1000 to 2000 hr can be expected. Today Globar resistors are provided with ends having an electric conductivity more than thirty times as high as that of the heating part. The high conductivity ends are held in a terminal clamp which, in turn, receives the current by means of a flexible terminal strap.

Globar resistors should be mounted to avoid any possible mechanical stress on the resistors. Figure 70 shows, on the left, a horizontal arrangement for Globar and, on the right, a vertical arrangement.
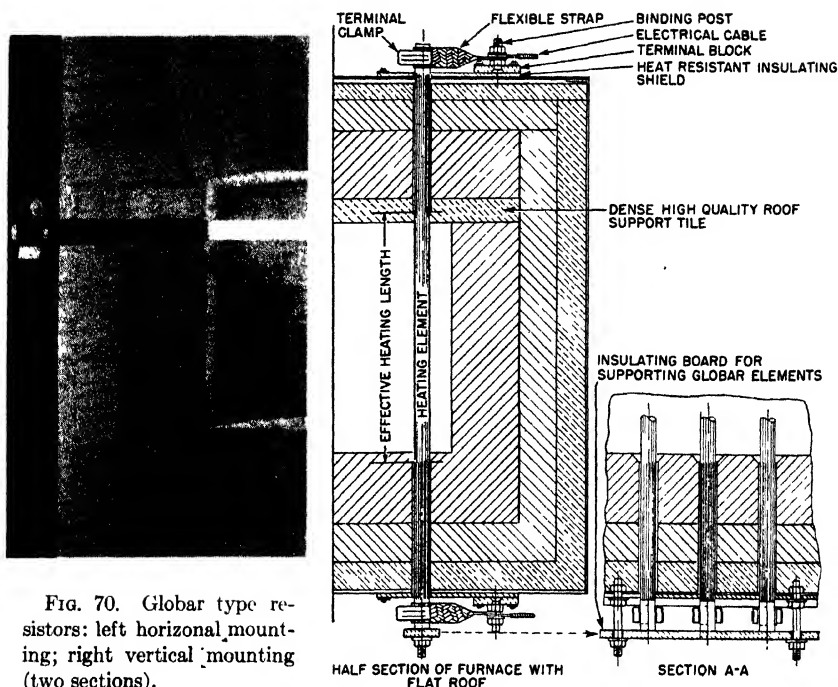
FIG. 70. Globar type re-
sistors: left horizonal mount-
ing; right vertical mounting
(two sections).

(d) Basis of Resistor Design

CONNECTED LOAD

Heating resistors are calculated and designed for a given electric load, which is designated as "connected load" or "input rate" and is measured in kilowatts.

The connected load for which a resistor should be designed depends on the rate of useful load and on the rate of heat loss. Other considerations include: the speed of heating up the furnace, accuracy of temperature control, and price.

In a furnace with steady uninterrupted flow of charge through the furnace (e. g., conveyor type) the rate of useful heat is constant in each location (section) in the furnace. In batch type furnaces or intermittently operated (e. g., pusher type) furnaces, the rate of useful heat flow changes with time. Calculation of the amount of heat absorbed by the charge at various times is possible only for fairly simple conditions.[31]

For the rapid recovery of the furnace temperature and quick heating of the charge, it is desirable to make the connected load so large that

[31] H. Gröber and S. Erk, *Die Grundgesetze der Wärmeübertragung.* Springer, Berlin, 1933, p. 48.

the useful heat of the batch could be supplied within 30 to 60% of the time allotted to one charge.

The rate of heat loss and the influence of the connected load on the heating-up are discussed in the section on wall design. No great savings in heating-up time of the empty furnace can be achieved by increasing the connected load beyond a certain value, which depends on the lining material of the wall and ranges from 1.5 to 3.0 kw per sq ft. In heating up load and furnace together from cold, the part of the connected load assigned to heat the wall need not be higher than the value of 1.5 to 3.0 kw per sq ft.

The accuracy of temperature control is greatly influenced by the connected load (see page 59).

The connected load influences the first cost in several ways: the switchgear becomes more expensive with increasing size and therefore a small change in connected load may result in selection of switchgear of a different group or size with appreciably different price. The cost of the transformer, if any, is influenced by the connected load; transformers with separate coils become more expensive with increasing size. With auto-transformers the relationship is not so simple (see page 52). The resistors become more expensive with increasing connected load, as discussed on page 88.

For batch type furnaces it is safe to select the connected load approximately 50% above the sum of the rate of useful heat + rate of steady state heat losses. For continuous furnaces a more accurate calculation of the connected load can be carried out for the various zones, based on their heat balances.

ENERGY DENSITY

The highest temperature in the resistor determines its life. The temperature of a resistor depends on the energy density (connected load per unit surface area), the temperature of the surrounding medium (furnace temperature), and its design. However, because of problems of mechanical strength and because minute surface irregularities are proportionally more important in thin than in heavy cross sections, thermal considerations, such as selecting energy density, do not constitute the only determining factors.

For the two most commonly used resistor types—ribbon resistors and wire coil resistors—Stansel [32] calculated the temperature differences between the surface of the charge and the resistor as function of the energy density. Figure 71 is drawn for a single strip of ribbon or a single piece of wire. In actual furnace design adjacent strips or wires influence each other mutually. Thus, to obtain a certain temperature difference,

[32] R. N. Stansel, *Gen. Elec. Rev.*, **31**, 662 (1928).

the energy density, i (w per sq in.), shown in Figure 71 must be reduced by correction factors, which depend on the geometry of the resistor and are given in Figure 72, where $g \times s$ is the length of the long side of a resistor ribbon and b the distance between two ribbons. These figures show temperature differences under ideal conditions (that is, with no obstruction to heat flow being encountered).
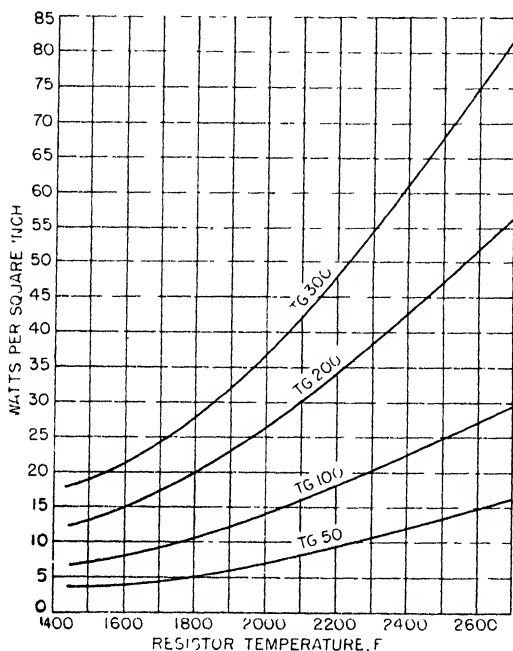

FIG. 71. Energy density for resistor ribbons. T.G. represents the temperature gradient between heater and heated surface.[32]

Practical values for surface load are as follows:

Temperature range, F	Energy density, w per sq in.
1000–1100	18–20
1400	13
1650	9
1850	6
2000	4.5
2100	2.6

For nonmetallic resistors, particularly Globar resistors, it is recommended that the energy density, i, be kept below a value expressed (in w per sq in.) by:

$$i = 300 - (t_F/10)$$

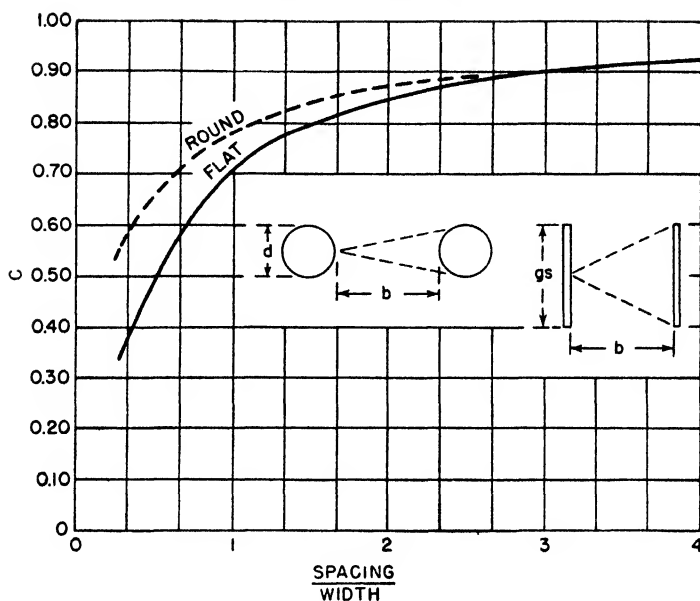where t_F is the furnace control temperature in F.

Fig. 72. Correction factors for proximity corrections. C = the ratio of obstructed radiation to free radiation.[32] Spacing/width = $b/d = b/gs$.

Example. For a control temperature of 2300 F keep the energy density below $i = 300 - (2300/10) = 70$ w per sq in.

(e) Calculation

DEVELOPMENT OF FORMULAS

If the energy density and operating voltage are given, diameter and length of the wire for round wire or strip resistors cannot be selected deliberately, but rather follow automatically.

Notations.

W = connected load (kw)
E = voltage (v)
R = resistance (ohm)
ρ = resistivity (ohm sq mil per ft)
i = energy density (w per sq in.)
p = perimeter (in.)
A_s = cross-sectional area (sq mil)
l = length of wire (ft)

A = surface area (sq in.)
w = weight (lb)
γ = density (lb per cu ft)
g = ratio of sides of rectangular resistors: large side/small side
d = diameter (in.)
s = smaller side (thickness) of rectangular resistor (in.)

Subscripts.

rec (equations refer to rectangular strip)
Y (refers to Y connection)
Δ (refers to delta connection)
|| (refers to two groups in parallel)
||| (refers to three groups in parallel, etc.)

Where no subscript is used equations refer to round wire, single-phase, one group.

The following equations are applicable for single-phase circuits of any cross section:

$$W = \frac{E^2}{R \times 10^3} \; ; \qquad R = \frac{\rho l}{A_s} \; ; \qquad A = 12pl$$

$$i = \frac{W \times 10^3}{A} \; ; \qquad w = \gamma A_s \times \frac{l \times 10^{-6}}{144}$$

Consequently:

$$A_s p = 8.33 \times 10^4 (W^2 \rho / E^2 i) \tag{15}$$

$$w = \gamma A_s \frac{W}{ip} \frac{10^{-6}}{1.728} \tag{16}$$

$$l = \frac{83.3 W}{ip} \tag{17}$$

For round resistors:

$$p = \pi d \qquad A_s = \frac{d^2 \pi}{4} \times 10^6$$

Hence Equations (15) to (17) can be written as follows:

$$d = \sqrt[3]{\frac{W^2 \rho \times 0.0337}{E^2 i}} = 0.323 \sqrt[3]{\frac{W^2 \rho}{E^2 i}} \tag{15a}$$

$$w = \gamma \frac{W}{i} d \frac{1}{6.912} = \gamma \times 0.0466 \sqrt[3]{\frac{W^5 \rho}{E^2 i^4}} \tag{16a}$$

$$l = \frac{83.3 W}{id\pi} = 81.9 \sqrt[3]{\frac{W E^2}{i^2 \rho}} \tag{17a}$$

For rectangular cross sections:

$$p_{rec} = 2s(1 + g)$$

$$A_s = s^2 g \times 10^6$$

Hence Equations (15) to (17) can be written as follows:

$$s = 0.347 \sqrt[3]{\frac{W_{rec}^2 \rho}{E^2 i_{rec} g(1 + g)}} \tag{15b}$$

$$w_{rec} = \gamma \frac{W_{rec}}{i_{rec}} \frac{sg}{1 + g} \times 0.29 = \gamma \times 0.10 \sqrt[3]{\frac{W_{rec}^5 \rho}{E^2 i_{rec}^4} \frac{g^2}{(1 + g)^4}} \tag{16b}$$

$$l_{rec} = \frac{83.3 W_{rec}}{i_{rec} \times 2s(1 + g)} = 120 \sqrt[3]{\frac{W_{rec} E^2_{rec} g}{i_{rec}^2 (1 + g)^2 \rho}} \tag{17b}$$

It is helpful to base the calculation of all resistors—including those of rectangular cross section—on the calculation of round resistors.

CHARTS FOR ROUND RESISTORS

Resistor calculations are repeated so often that it is desirable to develop charts and tables for this operation. Such charts are presented for round wires in this section, and for rectangular ribbons in the next.

The calculation of resistors is facilitated by alignment charts. From Figure 73 the diameter of the resistor is determined. Starting from
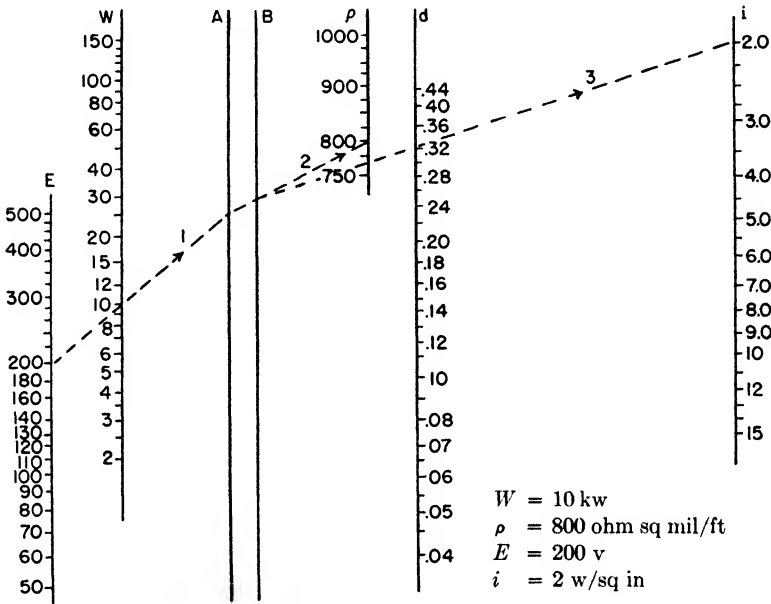

Fig. 73. Alignment chart for round resistors (diameter).

connected load and voltage, the sequence of operations is clear from the numbered arrows in the example. In drawing the last arrow, which starts at "support B" and connects diameter and energy density, the availability of resistor material should be kept in mind. The energy density is, by and large, a figure based on experience and can be shifted from the desired value in order to obtain a value of wire diameter which is being manufactured. After diameter and energy density are determined, length and weight can be found from Figure 74.

Example. $W = 10$ kw, $E = 200$ v, and $\rho = 800$ ohm sq mil per ft. By following the arrows, a value of $d = 0.323$ for $i = 2.0$ w per sq in. is read in Figure 73. Then, by following arrows $1a$ to $4a$ in Figure 74, a length $l = 400$ ft and a weight $w = 105$ lb is determined.

For medium and large furnaces the resistor dimensions as read from Figures 73 and 74 would be undesirable: very thick and short resistors

result. In such cases the total connected load should be distributed on two or more parallel branches. Applying a correction factor would eliminate the need for a repetition of the calculation.

If the number of parallel circuits is M_R, then the correction factor, k_p, is $\sqrt[3]{M_R^2}$. It is important that the same correction factor applies in converting the results from Figures 73 and 74 which hold for single-phase current. With a Y connection, $M_R = \sqrt{3}$; with a delta connection, it equals 3. The correction factors may be superimposed; for example, for a three-phase delta-connected furnace, with two parallel branches per phase, the correction factor k_p for $M_R = 3 \times 2 = 6$ must be used. Values for k_p for different values of M_R are listed in Table XII. The
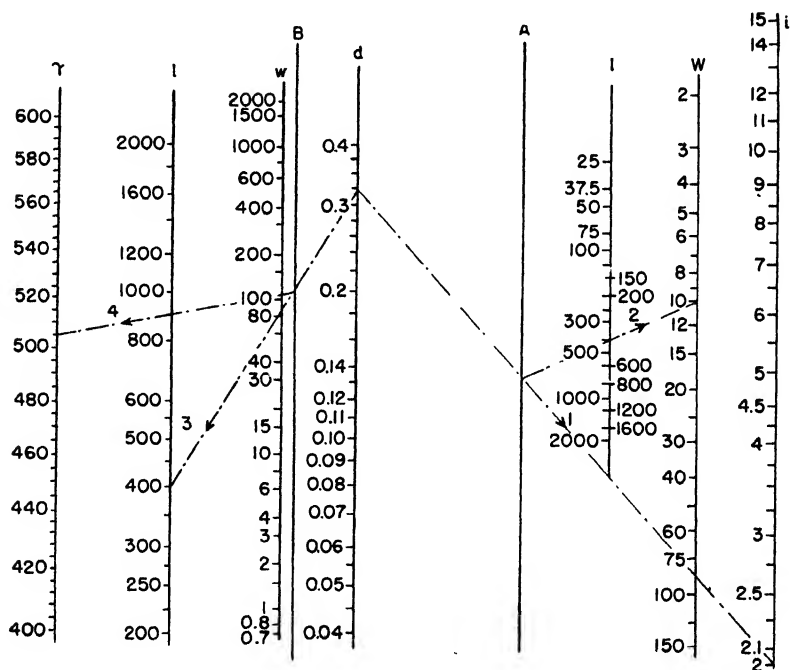

FIG. 74. Alignment chart for round resistors (length and weight).

correction factor is the same for length, diameter or side, and weight. In parallel circuits the side or diameter and the weight of the wire are decreased, the (total) length is increased.

Example. In the case of two parallel circuits and three-phase Y connection in the above example, the values for the resistors would have to be found by multiplying the factor for $M_R = 1.73$ (1.442) by that for $M_R = 2(1.587)$. Hence the factor for $M_R = 2 \times 1.73 = 3.46$ is $k_p = 2.288$. The diameter must

be $0.323/2.288 = 0.104''$; the length is $2.288 \times 400 = 915.2$ ft; the weight is reduced to $105/2.288 = 45.9$ lb. In the case of two parallel resistors, delta connection, the correction factor would be 3.302 (for $M_R = 6$).

<div align="center">

TABLE XII

VALUES OF k_p

</div>

M_R	k_p	Remarks
1.73	1 442	Three-phase Y connection
2	1.587	
3	2 080	Three-phase delta connection or three parallel circuits
4	2.520	
5	2.924	
6	3.302	
7	3.659	
8	4.000	
9	4.327	
10	4.642	
11	4 946	
12	4.970	

Equations (15) to (17) yield some important information:

(1) Increase of resistivity of the resistor material results in increased weight of the resistor, but in reduced total length. The quest for materials of high resistivity is therefore legitimate with respect only to limited space requirements, not to weight.

(2) The diameter decreases at the rate of the $\frac{1}{3}$ power, the weight decreases at the rate of the $\frac{4}{3}$ power, and the length at the rate of the $\frac{2}{3}$ power of an increase of energy density.

(3) Increase of side ratio (g) of rectangular shapes is very effective for cutting down weight and length. But of course a high value for g means a mechanically weak ribbon.

CHARTS FOR RECTANGULAR RESISTORS

Rectangular resistors can be calculated from the charts for round resistors (Figs. 73 and 74) by means of an adaptation chart (Fig. 75). The ratios of weights (W_{rec}/W_{ro}), of lengths (l_{rec}/l_{ro}), and of the smaller side to the diameter (s/d) are plotted as functions of g. (The subscripts "ro" indicate items for round resistor wire.)

Example. If in the example above the round wire is to be replaced by a rectangular strip with a side ratio $g = 5$, then:

$$s/d = 0.32 \qquad s = 0.32 \times 0.323 = 0.103 \text{ in.}$$
$$\text{(larger side)} \quad 5 \times 0.103 = 0.515 \text{ in.}$$
$$l_{rec}/l_{ro} = 0.755 \qquad l_{rec} = 0.755 \times 400 = 322 \text{ ft}$$
$$W_{rec}/W_{ro} = 0.58 \qquad W_{rec} = 0.58 \times 105 = 0.609 \text{ lb}$$

The cross section of the resistor ribbon thus determined may not be standard; then a new value g would have to be selected and the entire procedure repeated.

To avoid this inconvenience, from Figure 76 the cross section can be selected, from Figure 77 the length, and from Figure 78 the weight.

Example. Design a resistor for the following conditions: three phase, Y connection; total connected load $W_Y = 150$ kw; line voltage 640 v; energy density $i = 5$ w per sq in.; resistivity 980 ohm per sq mil, ft.
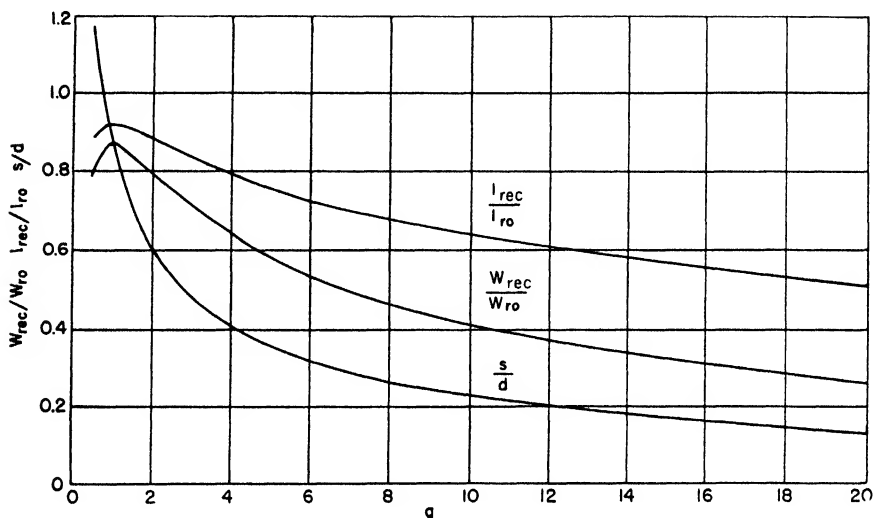

FIG. 75.   Adaptation chart.

Figures 76 to 78 are drawn for single phase. It is necessary to reduce the values of connected load and voltage to those for one branch before using the charts. Thus the voltage per branch is $640/1.73 = 368$ v. The power per branch is $150/3 = 50$ kw.

With Figure 76, start at 368 v on the E axis. Draw a line *1* through the correct point (50) on the W axis and extend line to "support A." Then draw line *2* to the correct point (980) on the ρ axis and mark intersection with "support B." From this intersection draw line *3* to the correct point (5) on i axis and mark intersection with "support C." From there draw a horizontal line *4* to intersection with the curve for the desired thickness (0.070 in.). From there drop a perpendicular line *5* showing on the abscissa axis the correct width $gs = 1.0$ in. Procedure on Figures 77 and 78 is similar. From Figure 77, following the arrows, the length (per phase) is found to be 390 ft; hence the total length is $3 \times 390 = 1170$ ft. The weight, finally, is found from Figure 78. Starting from the known cross section (1.0 × 0.070 in.) the known energy density, connected load, and the density of 570 lb per cu ft, the weight of 110 lb per phase can be found by following the arrows. The total weight for three phases is 330 lb.

If a combination occurs which is beyond the range of the charts, it is possible to use a different value (e. g., larger or smaller W or E) consistently and correct the results according to the formulas.
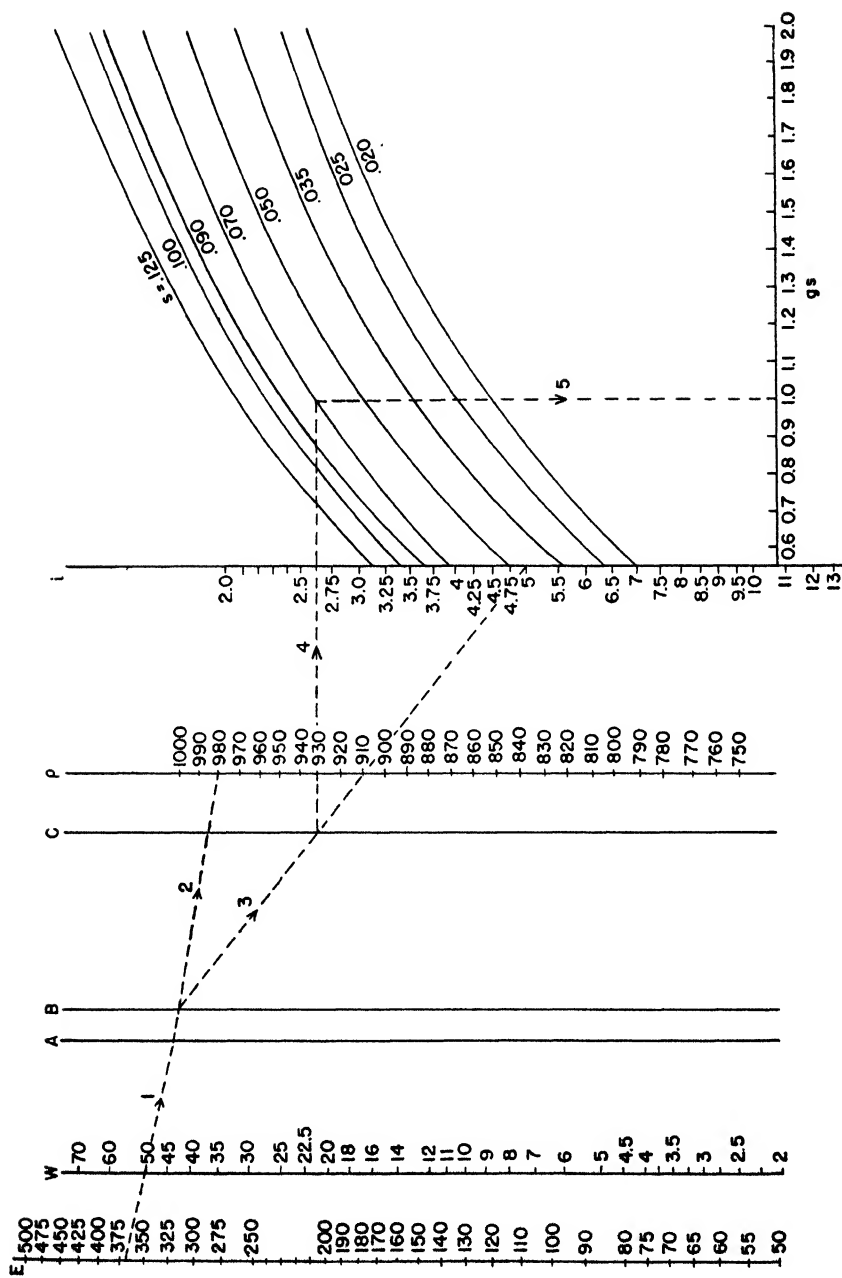
Fig. 76. Alignment chart for rectangular resistors (cross section).
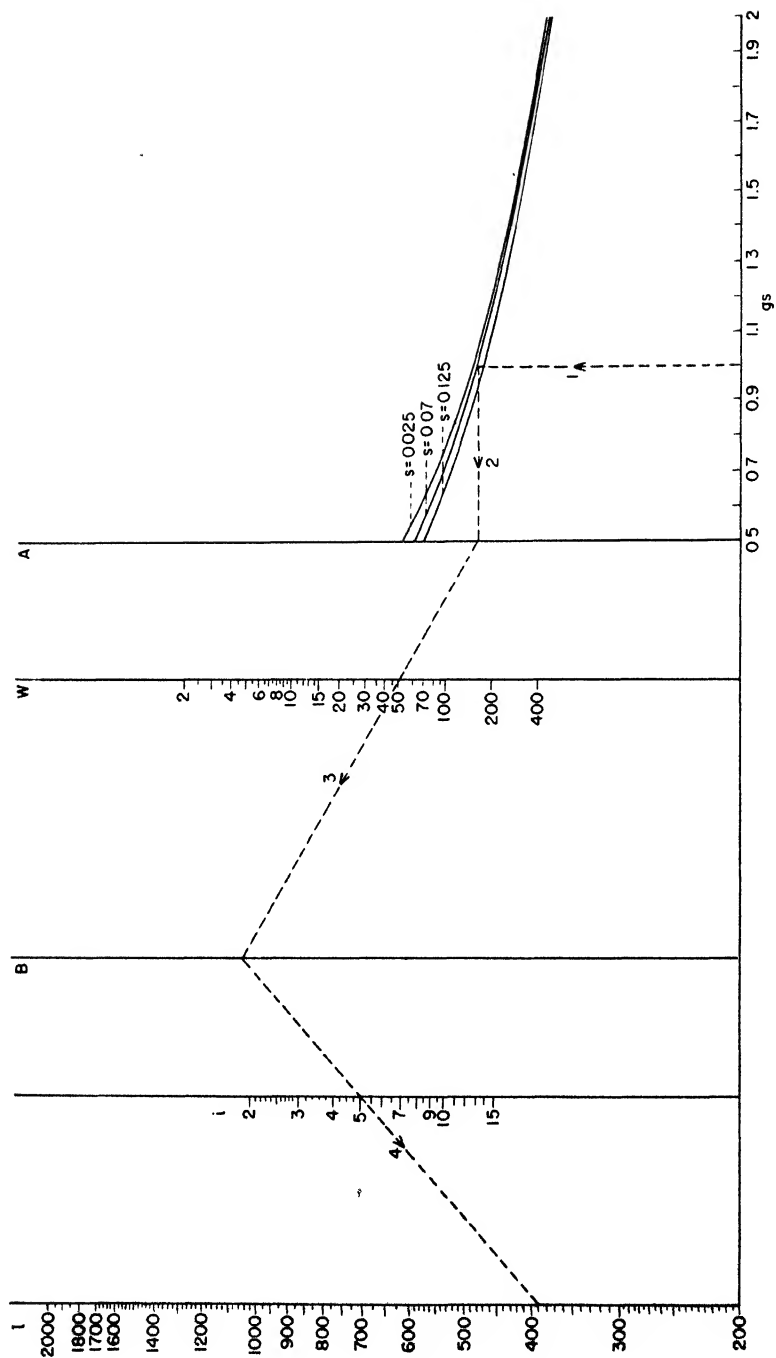
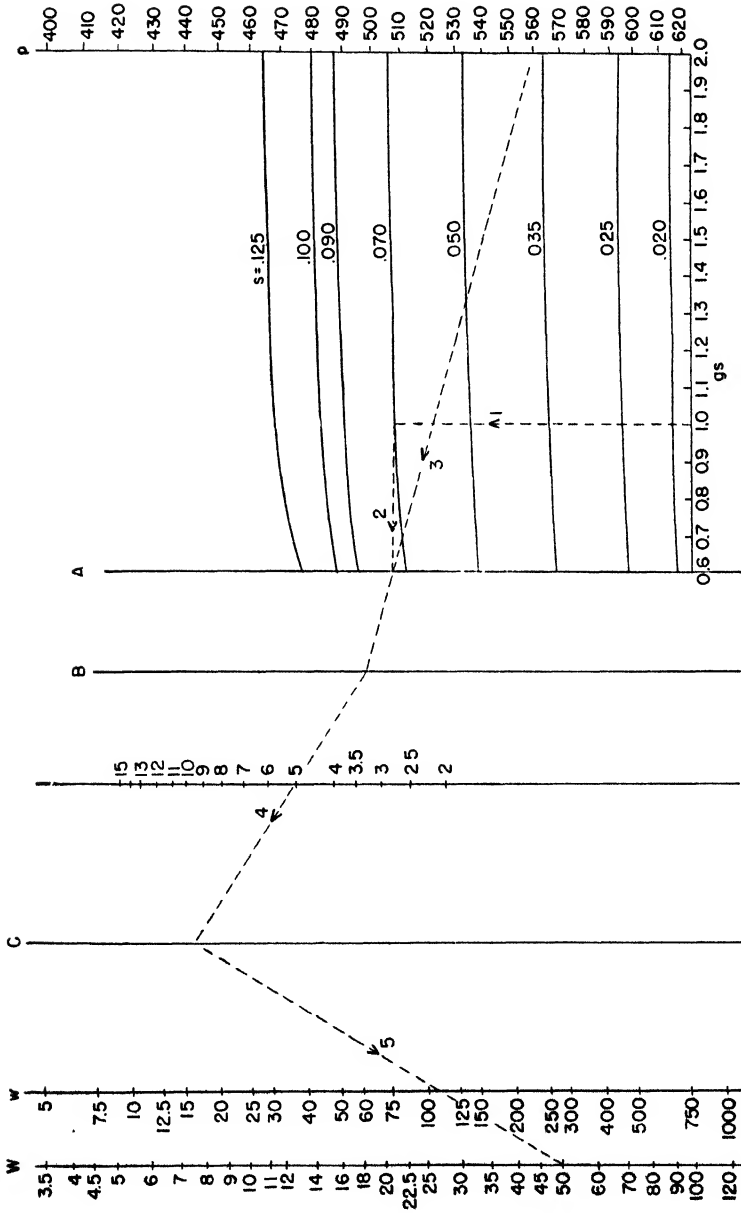FIG. 77. Alignment chart for rectangular resistors (length).

Fig. 78. Alignment chart for rectangular resistors (weight).

(f) Minimum Thickness

By putting more (see p. 90) circuits in parallel, the value of k_p can be increased to any desired value, and the weight reduced infinitely, finally approaching zero. Obviously there is a practical limit, below which the diameter or thickness is not safe.

Local overheating, which is to some extent always unavoidable, is more dangerous in thin than in thick cross sections, because the heat generated locally cannot be carried away. Unavoidable irregularities in the surface have proportionally a much larger effect in thin-section resistors than in thick-section ones.

The minimum thickness depends on the operating temperature and is listed below. Generally speaking, resistors with thick cross section have a longer life than thin resistors. Therefore it is sometimes recommended that considerations of energy density be disregarded and the heaviest wire possible be used; heavy wire entails of course great length of the wire, and space limits prevent use of too great a length. However, this reasoning is exaggerated, and selection of minimum thicknesses is a preferable basis of resistor design.

If the calculation based on the energy density figures shown on page 86 results in resistors thinner than the recommended minimum below, one of two means can be applied to remedy the situation: the energy density can be lowered below the recommended values; or a transformer can be used to reduce the applied voltage. Either method results in heavier cross sections for the resistor. Which of the two is applied depends on available space, the first method resulting in greater length of wire or ribbon than the second. For ribbon resistors, a change of g is a third means which may sometimes help.

Recommended minimum thicknesses for wire and ribbon are shown in Table XIII. Because of the wide variety of designs, changes of these

TABLE XIII

MINIMUM THICKNESSES FOR RESISTORS

Type of resistor	Temperatures, F, of resistor			
	<600	600–1300	1300–1900	>1900
Wire wound on frame	1/32	1/16	3/32	a
Wire, coils in wall recesses	1/16	3/32	1/8	3/16
Wire, coils on cores	3/64	3/32[b]	3/32[b]	a
		1/16[c]	1/16[c]	1/8
Ribbon, wound on frames[a]	1/32	1/32	1/16	a
Ribbons standing on edge on supports[d]	1/32	3/64	3/32	1/8
Ribbons suspended in loops[d]	3/64	1/16	1/8	a

[a] Design not recommended for this temperature.   [d] Straight wire wound helically on core (Fig. 66, left).
[b] Wire helix wound helically on core (Fig. 66, right).   [d] Recommendations hold for a side ratio of $g = 5$ to 6.

minimum values are sometimes desirable. The values should be adapted to individual designs.

2. Controlled Atmospheres

Old open-flame fuel-fired furnaces sometimes produced a good surface of the charge but more often caused failures in the form of surface oxidation or decarburization. When resistor furnaces were first introduced they were hailed as the solution to these troubles: no flames in the furnace chamber could cause any trouble; the furnaces were relatively tight, so that no air infiltration would occur, and thus all difficulties would be solved. Soon, however, it was found that this is not so. The atmosphere in the electric furnace was slightly oxidizing, in some instances causing considerable difficulties. These formed a starting point for a rapid development that took place in less than ten years, a development that has made the furnace designer and user "atmosphere conscious." The development influenced similar progress in fuel-fired furnaces, and research carried out with them benefited in turn the electric furnace design. Today the field of furnace atmosphere is highly perfected, although progress may still be expected. It is so complex a science that within the framework of this book no exhaustive presentation is possible.

(a) Survey of the Problem

CHEMICAL BASIS

Compositions of different gases which are stable at one temperature may be unstable at higher or lower temperatures. Therefore a gas suitable at one temperature may prove unsuitable at others. The equilibrium between carbon monoxide and carbon dioxide in an atmosphere containing no other gases changes as follows: [33]

Temperature, F	CO_2/CO
1600	0.055
1500	0.1
1400	0.25
1300	0.57

It is important to note that the equilibrium of gases depends not only on temperature, pressure, and gases present, but also on solids exposed to the gases. Whereas refractories may be attacked by the atmosphere, it is not generally assumed that the refractories influence the atmosphere to any appreciable amount. But the composition of a metallic charge has definite bearing on the equilibrium. The presence and nature of carbon in steel changes the equilibrium ratio of CO_2/CO.

[33] J. J. Turin, discussion of paper of H. W. Gillett and B. W. Gonser, in *Controlled Atmospheres.* American Society for Metals, Cleveland, 1942.

Consequently atmospheres required for different steels or metals are different.

REQUIREMENTS OF THE CHARGE

Special atmospheres in which to heat metals are necessary for two main reasons: first, to avoid oxidation, which can vary in degree from a more or less permissible discoloration of the surface to heavy scale coming off the metal in flakes; second, to avoid change of the surface composition of the metal, the most important case in point being the change of carbon content in steels. In most cases decarburization is the danger, but undesirable increase in carbon content is also possible. Such a change in composition may necessitate removal of the soft decarburized skin because decarburized metal cannot be hardened by quenching.

INFLUENCE OF FURNACE DESIGN AND OPERATION

Specifications based on equilibrium diagrams of a certain required atmosphere for a specific metal and operating temperature refer of course to the furnace chamber. Darrah [34] points out that the equilibrium, as perhaps prepared in the gas-producing unit, is continuously disturbed in the furnace proper. In a batch type furnace with relatively long heating cycle the furnace can be made fairly gas tight, so that the atmosphere once adjusted can be maintained. However, with changing temperatures the requirements change too, and hence readjustments may be necessary. For batch type work and short heating cycles, as in hardening, operation may be quite difficult, because every time the door is opened, there is an infiltration of air (sometimes even water vapor from adjacent baths) with consequent disturbance of the equilibrium conditions. In continuous furnaces conditions are still harder to control. Measurement and control of atmosphere should be that of the furnace working chamber, not that of the point of gas inlet or of the gas producing apparatus.

REFRACTORIES

It is known that furnace refractories stand up less well in certain protective atmospheres than when used in the slightly oxidizing atmosphere prevailing in the usual electric resistor furnace with no atmospheric control. Particularly CO seems obnoxious, although the same refractories show reasonable life in fuel-fired furnaces. Little is as yet known about these relationships. It appears that light-weight refractories show a better life than dense refractories,[35] but no explanation is available (see also page 35).

[34] W. A. Darrah, discussion of paper of H. W. Gillett and B. W. Gonser, *loc. cit.*

[35] J. H. Louck, *Trans. Am. Soc. Metals*, **28**, 877 (1940). See also W. L. Stafford, "Symposium on Furnaces and Kilns," ASME semiannual meeting, Pittsburgh, 1944.

(b) Methods of Excluding Gases

Consider any batch type electric heating furnace. In general the amount of air in the furnace chamber is not large enough to cause any trouble if no fresh oxygen is supplied. Moreover, during the heating period the air expands and therefore the slight positive pressure in the furnace chamber prevents infiltration of air. During the cooling period, however, air in the furnace chamber contracts; because of the air pushed out during the heating period by the positive pressure there is now a slight vacuum in the chamber. Since there is a tendency to suck in fresh air which would cause quick oxidation, some European designs are of interest which have been developed but not yet introduced into the United States. The Gruenewald process and some others less known are all based on the principle of letting the air expand during the heating period and preventing infiltration of fresh air during the cooling period.[36] The charge is placed in a tight container provided with a one-way valve. During the heating period the air in the container expands and because of the resulting pressure is pushed out through the valve. Thus the amount of oxygen that may attack the load is greatly reduced. During the cooling period, when the air in the container contracts and outside air tends to be sucked in, the one-way action of the valve will prevent the entrance of air. In some designs a protective gas is admitted to the container at this stage.

This method of heating is of course applicable only to heat treating processes, such as annealing processes, in which the charge cools in the furnace, not to hardening, forging, or brazing procedures. Moreover, only rarely, even in annealing, is entirely bright material produced by this method. The small amount of air remaining after the heating period usually causes at least slight discoloration.

(c) Types of Gases for Ferrous Metals

There are three main types of protective gases: products of partial combustion and/or cracking of fuels; mixtures of hydrogen and nitrogen (mostly cracked ammonia); and technically pure gases (hydrogen, nitrogen, helium).

GASES RESULTING FROM PARTIAL COMBUSTION OR CRACKING OF FUELS

If fuels are heated in the presence of oxygen, heat is liberated and CO_2 and N_2 are generated. With an excess of air not all the oxygen of the air is used up, and thus, in addition to CO_2 and N_2, free oxygen is available. With insufficient air, unburnt carbon monoxide is also present. If fuels are heated with no or very little air present, they "crack" and

---

[36] See, for example, H. G. Kloninger, G. Keller, and H. Meuche, *J. Inst. Metals*, **46**, 537 (1936).

various gases are produced, depending on the nature of the fuel and the temperature to which the fuel is exposed. Cracking is an endothermic process: heat must be supplied from an outside source for the chemical reactions taking place.

The fuels used for the production of protective gases may be either gaseous (natural or city gas, butane) or solid (charcoal) or liquid (benzol). The resulting gases are, generally speaking, mixtures of CO_2, CO, H_2, N_2, O_2, H_2O, and hydrocarbons (CH_2, CH_4, etc.). In order to obtain the desired results it is necessary to eliminate water vapor, which even in small quantities oxidizes the surface; elimination of water vapor may be done by polymerization and cracking or by drying. The apparatus to
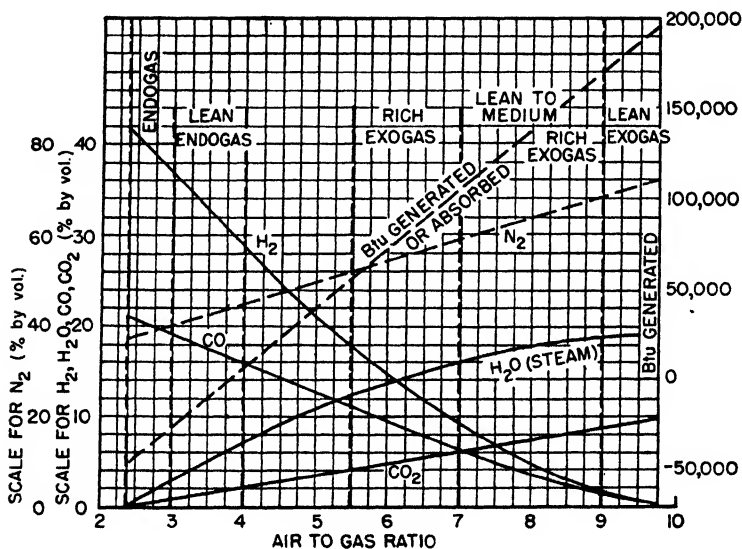
FIG. 79.   Composition of gases obtained from methane.[37]

do either will be briefly described in a later section. The degree of drying in connection with protective atmospheres is generally expressed by the dewpoint. A dewpoint of a degrees indicates that if the gas is cooled to this temperature the moisture appears in liquid form.

As the air/fuel ratio decreases, the amount of liberated heat drops, and below a certain value no heat is liberated but heat must be supplied (cracking). Figure 79 shows the composition of gases obtained from methane,[37] and Figure 80 that of gases obtained from coke oven gas.[38]

[37] C. E. Peck, *Ind. Heating*, **10**, 336, 479, 799, 951, 1118 (1943); *Trans. Am. Soc. Mech. Engrs.*, **67**, 501 (1945).

[38] A. G. Hotchkiss and H. M. Webber, in *Controlled Atmospheres*. American Society for Metals, Cleveland, 1942.

The former also shows the heat of reaction, liberated (above the zero line) or necessary (below the zero line).

MIXTURES OF HYDROGEN AND NITROGEN

These mixtures are obtained by cracking anhydrous ammonia. Complete cracking results in an atmosphere composed of approximately 75% H_2 and 25% N_2. By inserting air, then burning part or all of the hydrogen, and subsequently drying, almost any ratio H_2/N_2—up to the maximum of 3—can be obtained.

TECHNICALLY PURE GASES

Since, for economic reasons, helium and similar rare gases are not applied in industrial furnaces, only technically pure hydrogen and nitrogen remain in this group. Pure hydrogen is less used in the United States, but has found extensive application abroad.[39] It is com-

Fig. 80. Composition of gases obtained from coke oven gas.[38]

bustible, and if a mixture with oxygen occurs before heating this mixture is a very potent explosive. It is usually purchased in bottles, except for large installations for which local production of the gas by electrolysis may be economically feasible.

Nitrogen as bought in bottles usually contains sufficient oxygen to cause damage to the charge. It is more conveniently produced either from burnt fuels or from cracked and burnt ammonia. In the first case, by complete combustion of a fuel, a gas mixture is prepared, and carbon dioxide is then eliminated by chemical treatment. In a similar way cracked ammonia is completely burned; the product of combustion when dried is pure nitrogen.

APPLICATION OF GASES TO FERROUS METALS

Steels containing chromium must not be treated in atmospheres with carbon monoxide or carbon dioxide components but only in hydrogen, nitrogen, or mixtures of both.[40] Carbon steels and steels with alloying elements other than chromium can be treated in any one of the three above-mentioned groups of atmospheres.

Selection of the atmosphere must take into consideration the two points already mentioned: avoiding decarburization and avoiding oxidation, the latter possibly extending to reducing oxide layers existing at the start of the heating process.
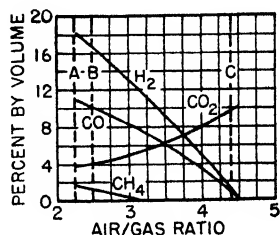
[39] T. Stassinet, *Stahl u. Eisen*, **49**, 1509 (1929).

[40] D. Dahl and F. Pawlek, *Stahl u. Eisen*, **60**, 137 (1940).

Gases containing only carbon monoxide and nitrogen are in most cases safer than those containing also carbon dioxide and traces of water, but they are more expensive. They are necessary for annealing high-carbon steels and alloy steels, and for bright hardening and brazing of medium- and high-carbon steels and alloy steels. Only low-carbon steels can be successfully annealed in atmospheres containing appreciable amounts of carbon dioxide. However, cases are known [38] in which small amounts of water vapor and carbon dioxide were necessary to avoid discoloration.

(d) Types of Gases for Nonferrous Metals

Generally speaking, nonferrous metals, in particular copper and copper alloys and aluminum, magnesium, and their alloys, are less sensitive to atmosphere composition than are steels.

Pure copper can be bright annealed in steam; here, however, difficulties arise in cooling, particularly when coils or piles of sheets are being treated. The steam between the layers condenses and the water produced causes local discoloration on the copper. Hydrogen in any concentration above 1% is injurious to copper containing cuprous oxides.[41] Free oxygen even in minute traces—causes discoloration. Sulfur, of which there may be traces in the fuel used for preparing the protective atmosphere, is dangerous, particularly in the form of hydrogen sulfide. With these restrictions it can be stated that the gases described for use of steel and those produced by combustion and cracking of fuels can be used.

It should be noted that brass can be only "clean annealed," not "bright annealed," because, even if no oxidation takes place, zinc evaporates at elevated temperatures, leaving the surface of the brass rough and therefore devoid of bright appearance.

The heat treatment of aluminum and its alloys, except aluminum–magnesium alloys, does not call for special atmospheres.[42] Magnesium and alloys containing appreciable amounts of magnesium should be treated in protective atmospheres; this method makes possible an increase of heat treating temperature. The preferred atmosphere for magnesium and its alloys contains several tenths up to 1% sulfur dioxide. Hydrogen is permissible but nitrogen has not as yet been investigated sufficiently.

(e) Types of Gases for Nonmetallic Materials

Not only metals, but also some ceramic materials, must be fired in special atmospheres to obtain certain color effects. Little is as yet known

[41] E. G. de Coriolis and W. Lehrer, in *Controlled Atmospheres*. American Society for Metals, Cleveland, 1942.

[42] P. T. Stroup (page 207) and C. E. Nelson (page 221), in *Controlled Atmospheres*. American Society for Metals, Cleveland, 1942.

about atmosphere requirements in ceramic furnaces, because ceramic materials so far have been heated mainly in fuel-fired furnaces, which do not permit atmosphere control. In these no exact control of the atmosphere is possible because their atmosphere is adjusted empirically by the operator. Gould [43] made introductory studies on the influence of atmospheres on certain types of china. Masukowitz,[44] Meuche,[45] and Buchkremer [46] reported on atmospheres in large ceramic kilns operated in various countries abroad (see also page 147). Andrews and Hertzell [47] report on the influence of gases on the quality of porcelain enamel and point out the danger of sulfur.

(f) Gas Consumption

It is impossible to give general information on the atmosphere gas consumption for various applications. Continuous and batch type furnaces for the same output and same product consume different quantities of gas.

In batch type furnaces practically the entire amount of gas in the furnace is lost at every change of charge; when, after the change of charge, gas is again admitted, it must expel the air in the working chamber. Air is also frequently trapped in the lining and even in the conveying mechanism. The charge itself carries air into the furnace. Purging the furnace chamber of all the air takes four to five volume changes. Once the air is removed, the gas consumption is fairly low. A small gas stream is supplied permanently, in order to maintain a positive pressure in the furnace. For combustible gases it is also desirable to have the escaping gases burn permanently with a small flame, so that the operator knows that the gas supply is operating. Leakage through the seal is unavoidable. Hotchkiss and Webber [38] indicate an average figure of 5 cu ft per hr per linear foot of seal.

In continuous furnaces with one or more openings, the gas consumption is proportional to the pressure difference between furnace and shop, and to the area of the opening. Because of the considerable amount of gas thus consumed, it is convenient to use flow resistances, chain or cloth curtains for example. The best solution for minimum gas consumption is to move the load in regularly intermittent steps. Then, during the stops of the load, closed doors can be applied and arrangements can also be made to prevent simultaneous opening of the doors on both sides of longitudinal chamber; this avoids a strong current of cold air. In addi-

[43] R. E. Gould and M. G. Tule, *Trans. Electrochem. Soc.*, **70**, 111 (1936).

[44] H. Masukowitz, *Elektrowärme*, **4**, 245 (1934).

[45] H. E. Meuche, *Electrotech. Z.*, **59**, 1317 (1938).

[46] H. Buchkremer, *Ber. deut. keram. Ges.*, **19**, 113, 271 (1938).

[47] A. A. Andrews and E. A. Hertzell, *Univ. Illinois Bull.*, **27**, No. 52 (1930).

tion, locks that seal the furnace proper while an outside door is opened can be used for this type of work. The amount of gas lost during each opening of the door is thus limited to the volume of the lock.

(g) Apparatus for Producing Gas

Equipment for the manufacture of gases consists in a unit for heating the fuel, either using its own heat (for combustion) or using extraneous heat (for cracking). Further units serve for the elimination of undesired components (carbon dioxide, for example) and for cooling and drying. Of course the attempt is made to combine the various units into a self-contained apparatus. It is impossible to describe all devices that are available. Reference is made to various articles dealing either with a group of generators or with one specific product.[48]
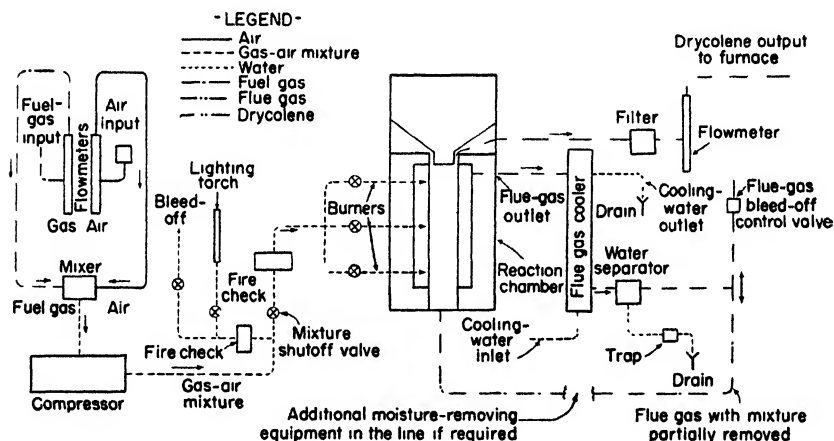
FIG. 81.   Flow diagram for atmosphere producer.   (Courtesy *General Electric Company*.)

As an example, see Figure 81, which represents a flow diagram for a unit producing a mixture of carbon monoxide, hydrogen, and nitrogen. The unit must be supplied with a hydrocarbon such as coke oven gas or natural gas ("fuel gas" in flow diagram). Gas and air are measured (flow meter), mixed and compressed, and then burned; the burners are located in a reaction chamber, in which the heat is generated by the combustion of fuel gas used to heat a charcoal bed. The product of combustion of the fuel gas, marked as "flue gas" in the flow diagram, is cooled and thus partially dried. The flue gas is then passed over the charcoal bed and heated as described above to incandescence.

[48] C. E. Peck, *Ind. Heating*, 10, 336 (1943). A. N. Otis, *Gen. Elec. Rev.*, 39, 601 (1936). N. K. Koebel, *Industrial Controlled Atmospheres*, Lindberg Engineering Co., Chicago, 1941.

Thus the protective gas, marked as Drycolene, is formed. After passing through a filter to remove solid particles it is ready for the furnace.

In recent years the instrumentation of atmosphere generators has made considerable progress. A review of the art has been given by Slowter and Gonser.[49]

Measurement and control can be accomplished either by chemical analysis of the entire gas or by determination of the quantity of one or two important components; or a physical property of the gas may be used (for example, electric conductivity), or the change of a physical property of a body exposed to the gas (e. g., resistance of a test wire). Because of the complexity of operation, automatic control of atmosphere composition is not yet highly developed. The instruments mentioned before are chiefly for indicating and recording.

In this connection it may be well to consider for a moment the means by which the user of a furnace can determine whether the atmosphere is efficient. If it is certainly nonscaling, the problem resolves, with steels, to questioning whether the atmosphere is carburizing or decarburizing the steel. Koebel[50] has studied this field and reported his findings. He describes four methods for determining the efficiency of atmospheres for steels: the hardness test; the photomicrographic approach; chemical analysis of consecutive cuts; and measuring change of density. In a definitely nonscaling atmosphere, the weighing method seems to be most advantageous; otherwise the analysis of consecutive cuts is best. The hardness test is the simplest but is not entirely reliable for judging the atmosphere. The advantages and disadvantages as well as the necessary techniques are described in detail by Koebel.[50]

(h) Cost of Gas

The cost of protective atmospheres varies within very wide limits. Nature of the gas and quantity used are among the determining factors. Slowter[51] has analyzed the first cost of equipment and the operating cost. He reports the following limits: unit investment costs vary from $0.45 to $60.00 per cu ft per hr capacity; operating costs from $0.07 to $4.10 per 1000 cu ft of atmosphere produced. Figures 82 and 83 are indicative of his presentation, which is summarized in Table XIV. Atmospheres used to change the property of the charge, as for carburizing or nitriding, are also considered, along with the furnaces in which they are used.

[49] E. E. Slowter and B. W. Gonser, *Metal Progress*, **38**, 555 (1940); **39**, 560 (1941).

[50] N. K. Koebel, in *Controlled Atmospheres*, American Society for Metals, Cleveland, 1942; *Industrial Controlled Atmospheres*, Lindberg Engineering Co., Chicago, 1941.

[51] E. E. Slowter, in *Controlled Atmospheres*. American Society for Metals, Cleveland, 1942.

TABLE XIV
SUMMARY OF ATMOSPHERE COSTS [a]

| | Atmosphere | | | | | Atmosphere costs | | | | | |
| | Nominal atmosphere composition % | | | | | Smallest unit 100–500 cu ft per hr | | 1 000 cu ft per hr unit | | 5 000 cu ft per hr unit | |
Equipment	CO_2	CO	CH_4	H	H_2O dew point I	Unit equipment cost $ cu ft hr	Operating cost $ 1000 cu ft	Unit equipment cost $/cu ft/hr	Operating cost $/1000 cu ft	Unit equipment cost $/cu ft/hr	Operating cost $/1000 cu ft
For atmosphere production											
Cracked NH_3	0	0	0	75	−40	7 75	4.10	3.10	4.07		
N_2 from cracked NH_3	0	0	0	0	80	10.20	2.58	5.00	2.56		
Charcoal gas[b]	0	34	0	0	−25	6.60	0.45	4.30	0.45		
Cracked gas	0	20	1	41	−20	11.60	0.43	3.75	0.26		
Partly burned gas	4	11	0.5	11	80	3.80	0.09	2.10	0.09	0.85	0.09
gas	11	0.5	0.5	0.5	80	3.80	0.07	2.10	0.07	0.85	0.07
Partly burned gas	Either low or high						0 01		0.01		0.01
gas	ratio gas				40	7.80	Addn	3.30	Addn	1.25	Addn.
Partly burned gasoline					60	1.50	0.20	1.25	0.20		
Partly burned gas with recirculation	1	12	1	5		6.50					
N_2 from partly burned gas	0	0	0	0	−40	60.00	0.27	9.00	0.27		
CO_2 removal by hot carbon	0	18	0	2	−30	7.00	0.18	4.25	0.19		
For atmosphere treatment											
Cooler	Cools to 40° F					2.70	0.01	1.10	0.01	0.40	0.01
Drier	Dries to −40° F					3.80	0.03	0.90	0.01	0.45	0.01
CO_2 scrubber	Electrically heated					6.00	0.14	4.30	0.13	1.90	0.11

[a] L. E. Slowter, in *Controlled Atmospheres* American Society for Metals, Cleveland, 1942.
[b] Prices include furnaces

3. Doors

Since design of door, door opening, door jambs, and front plate against which the door leans are mutually interrelated, all four will be discussed in this section.

Doors for radiation type furnaces should satisfy the following requirements: tight closure; sufficient overlapping; ease of operation; light weight; avoidance of wear, particularly abrasion; opening as small as possible; durability (avoidance of warpage); low heat loss. Small furnaces usually have hand operated doors, whereas medium and large

furnaces often have power operated doors (motor, compressed air, or hydraulic).

The size of the door opening is in most instances prescribed by the load. The opening is usually somewhat smaller than the inside chamber, thus protecting the resistors. In some instances, for long furnaces, inside furnace repairs must be considered; door openings are made large enough to permit a repair man to crawl into the chamber. Generally this is not
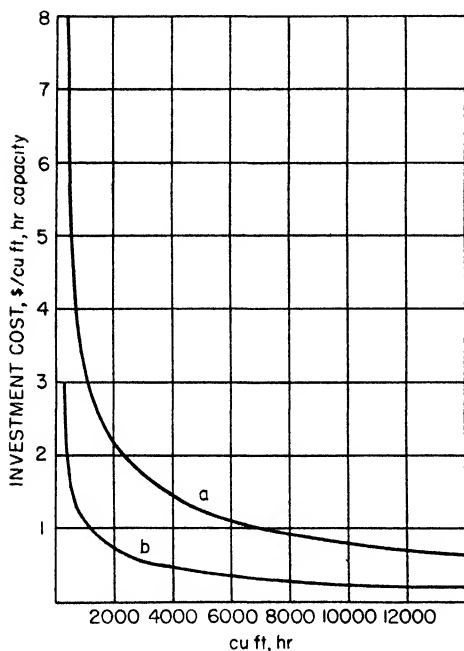
FIG. 82. Unit investment cost of gas producers (partial combustion).[51] Curve a, total unit cost; curve b, part of total unit cost used for refrigerating unit.
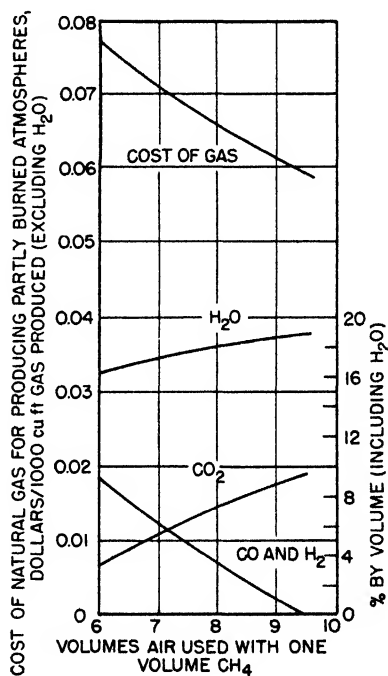
FIG. 83. Operating cost of gas producers.[51]

good practice. The accessibility of the inside should, whenever possible, be achieved by means other than increasing the door opening. In some instances the door opening is made sufficiently large to permit a man to crawl inside, but stops prevent the door in normal operation from uncovering the entire opening. Only when repairs are needed are the stops withdrawn. The desire for much overlapping and for light weight doors are contradictory. A compromise must be sought. An overlapping of $2\frac{1}{2}$ in. on every side should be considered minimum, 5 in. preferable, and more than $7\frac{1}{2}$ in. ordinarily useless. Overlapping results in tightness

and in considerably lower heat losses.   This may be understood from
Figure 84.

The weight of the door is important because of its influence on the
opening mechanism and heat storage.   Metal frame and lining contribute
to the weight.   The frame is cast or made of structural steel, the latter
being avoided by some designers because of the danger of warpage.   To
keep the weight of the lining low, thin monolithic linings are used, backed
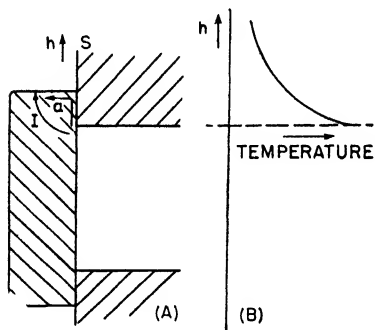
Fig. 84.   Overlapping of door.   Lowering of heat losses stems from two causes: (A) the heat loss through the top and bottom of the door is lessened because greater overlapping increases length of path for heat flow I; (B) the temperature of the surface, S, of the frontwall of the furnace drops sharply in direction h (see B).   The greater the distance a, the greater is the high temperature part of the furnace front, which receives additional protection.

by light-weight insulation.   The monolithic block forming the one surface
must be held in position, either by hooks, bolts, etc. (Fig. 85, left) or by
appropriate grooves (Fig. 85, right).

The insulation behind the lining consists usually of insulating bricks,
but sometimes the good European practice of using powder is also found
in the United States.   If the door is properly designed no powder can
escape; this danger of escaping powder
is usually given as the reason against
its use.   The use of powder results in
lighter lining, allowing a lighter frame,
faster operation, and lower heat loss and
heat storage.

The main source of wear of the
door is abrasion during opening and
closing.   Abrasion can be minimized
by providing guides which lift the door

Fig. 85.   Door design.

off the front plate immediately after the start of the opening move.
This can be done by inclines, wedges, rolls, or levers.

An efficient means of cutting down heat losses is the use of two doors,
one being placed in the door jamb, the other applied in the conventional
way on the outside.   The inside door acts as radiation shield and cuts
down draft.   The use of such double doors therefore tends to improve
considerably the temperature uniformity in the furnace chamber.
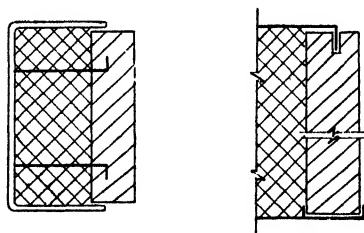
The front plates of a furnace are sometimes set on an angle, instead of being perpendicular. Thus the weight of the door rests naturally on the plates. The same result can be achieved by local inclines. In Figure 86, a door is being pressed against the front plate by inclines. The position of the sprocket permits the door to clear the front plate when lifted. A counterweight provides easier movement and is used also if the door is motor operated. Complications by counterweights, etc., are avoided by a design in which the door swings around vertical pivots (see Figure 87). Small doors are often made to swing open around a horizontal line.
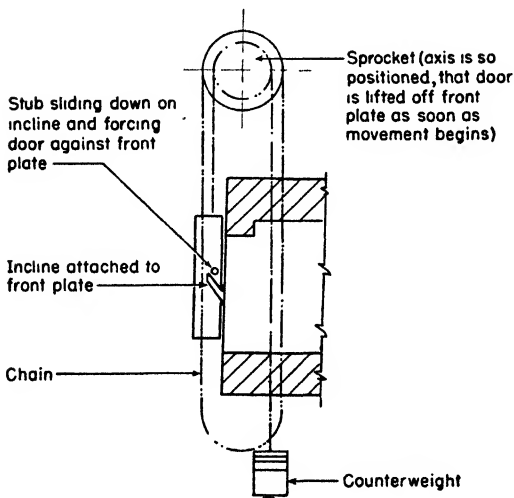
FIG. 86. Use of inclines for door tightening.
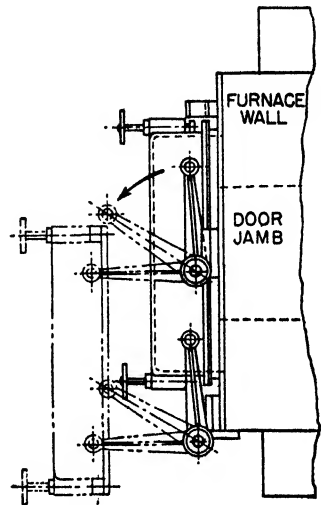
FIG. 87. Door swinging around vertical pivots (plan view).

C. PARTS FOR CONVECTION TYPE FURNACES

1. Resistors

The calculation of resistors is not different from that for radiation type furnaces. Resistors are located either in the working chamber or outside in separate air heaters. In the latter case the air velocity can usually be raised high enough to allow very much higher energy density than in resistors of radiation furnaces. If the entire length of the resistor were cooled by the air stream, the permissible energy densities would be exceedingly high, in some instances several hundred watts per square inch. However, the supports of the wire in all instances baffle the heater and therefore the parts of the wire in contact with the supports can lose their heat only by conduction. In view of this limitation, air heaters are not

loaded to much more than perhaps 25–50 w per sq in.   The resistors are usually arranged in frames, so that they can be withdrawn in units.

If the air supply fails, the resistors overheat very rapidly and melt; it is good practice to provide a safety switch which disconnects the resistors as soon as the fan fails.   The switch can be energized by the current of the fan motor or by the change in air pressure.

If the resistors are within the furnace chamber, so that they are in part radiating, it is good practice not to rely on the added heat transfer by convection but to base the calculation on radiation alone.

In treatment of combustible or explosive material, as in drying of lacquers, it is desirable to use entirely embedded resistors; even if a resistor should break, no spark can form and thus ignite the gases.   Such a precaution will be effective only if it includes the connections; the shield or enclosure must be brought through the wall of the oven and the connecting leads come out of the enclosure only outside the furnace.   This precaution should be applied for partly recirculating explosive gases with heaters in a separate chamber.

2. Fans

To achieve rapid heating with good uniformity in convection type furnaces, great quantities of atmosphere must be moved at high velocities. This procedure calls for large blowers.   However, radiation furnaces are sometimes equipped with auxiliary fans that serve to circulate the air and thus help to achieve uniformity.   In such furnaces fans are much smaller.

In the pure convection type furnace the blower is frequently, though not always, outside the furnace chamber.   The blower must always be built for the maximum operating temperature of the furnace.   This brings up the questions of oxidation of the fan and of creep strength. Thus convection type furnaces are limited to temperatures of approximately 1600 or 1700 F, although occasionally they are used at higher temperatures.   Large blowers used in pure convection type furnaces usually have an axial intake and a radial-discharge of the air, the blades being arranged in planes parallel to the shaft.   For high temperatures, blades and casing are made of heat resisting alloys; for lower temperatures, blades of steel are used.   Bearings call for special attention.   Except for low temperatures (even for work up to perhaps 350 or 400 F), bearings must always be removed from the hot zone.   Bearings of fans for higher temperatures must be cooled, even if located outside the heated zone, because heat is carried by conduction from the wheel through the shaft to the bearing.   Cooling is done either by water or by air.   Air cooling can be carried out by means of hollow shafts, or by putting an auxiliary fan on the shaft, between furnace shell and bearing (Fig. 88).

Thus the shaft is freed from the heat carried out of the furnace before the heat can reach the bearing. As far as mechanical properties permit, the shaft should be made of material with low thermal conductivity. The wall opening for the shaft should barely clear the shaft in order to avoid leakage of hot air from the furnace. If the shaft penetrates the furnace vertically, a water or oil seal can be readily applied. Otherwise the application of a seal will cause high friction.

Special precautions should be taken to continue cooling after stopping operation of the furnace, or the heat stored in the furnace wall may gradually reach and destroy the bearing.

Radial flow fans used for pure convection furnaces are being built for static pressures (at 70 F) up to 15 or 20 in. delivering (again referring to 70 F) up to 20,000 to 40,000 cu ft per min, depending on pressure.

For combined radiation-convection furnaces, very much lower static pressures are used than for pure convection heating, and hence axial flow blowers (disk or propeller type fans) may be used. These produce static pressures up to $\frac{3}{4}$ in. or 1 in. and

Fig. 88.   Auxiliary fan for cooling of blower shafts: F, fan; S, shaft; FW, furnace wall; B, bearing; P, packing against leakage; AF, auxiliary fan; I, intake for auxiliary fan; ah, airholes in shaft to cool bearing.

can deliver perhaps 20,000 to 30,000 cu ft per min at $\frac{3}{4}$ in. and up to 150,000 cu ft per in. at lower pressures. (All figures refer to 70 F.)

In selecting type, size, and dimensions of fans for furnace work, the pressure drops and the desired quantity of air are first determined. These calculations are discussed on pages 170–172. In applying the values found in performance or capacity tables issued by fan manufacturers, it must be kept in mind that the tables are set up for standard air conditions. The static pressure for a given velocity of air is inversely proportional to the absolute temperatures. Inasmuch as the necessary energy to drive a fan is proportional to the static pressure and to the square of the volume (cu ft per min), the necessary energy (hp) increases at a rate proportional to the ratio of absolute temperatures. Inasmuch as the efficiency of the

blowers is different, depending on size and pressure, the aforementioned relationship is only approximately correct.

D. PARTS FOR CONDUCTION TYPE FURNACES

1. Electrodes

In electrode salt bath furnaces, transformation of electric into heat energy takes place in the salt. The electric energy is brought into the salt by means of electrodes, and is transformed into heat in the salt between the electrodes. This heated salt is continuously removed from between the electrodes and then serves to heat all parts of the bath. Little is known concerning the mechanism of this transfer. With one exception (Upton furnaces, see page 185), electrodes are suspended in the bath from the top.

(a) Material

The material for the electrodes is selected on the basis of operating temperature and salt composition. For temperatures up to 1500 or 1600 F, firebox steel or pure iron (Armco iron) is used frequently. Sometimes for these temperatures and almost always for higher temperatures (1900 F) alloy steels are used, particularly chromium-iron alloys; nickel generally does not stand up well and is frequently avoided but is sometimes used for very high temperatures.

(b) Types

Electrodes are subjected to a certain amount of wear. Their spacing from each other and from the wall are of great importance for the performance of a salt bath furnace. Therefore, the electrodes are almost always so mounted as to be easily adjustable. In some instances the electrodes, suspended vertically in the bath, are welded to a horizontal leg attached to the shell of the furnace (Fig. 89). The leg is used to support the electrode and insulate it from the furnace shell. For this purpose electrode E is fastened down by clamps C against support S, using insulation I. Sometimes the entire support is placed on a bracket, A, dotted in Figure 89. The outside end of the leg is drilled to allow easy attachment of busses for connection with the transformer. This method of suspending the electrodes provides for sufficient play to allow lateral adjustment. If replacements are necessary, a new electrode is welded to the same horizontal leg, which may be used repeatedly. In some instances electrodes wear off fairly uniformly over the entire length, sometimes they "pencil" at the bottom, and sometimes they burn off near the salt level. The differences in behavior are attributable partly to properties of the salt, but in part to slight inaccuracies in assembly. If

the electrodes are closer at the bottom than at the top, the salt resistance there is smaller and the temperature at the bottom may rise unduly.

In furnaces in which the electrodes usually wear off at the salt level, another design is frequently employed (Fig. 90). The electrode is continuously fed into the furnace and receives current through a wedge arrangement. The main disadvantage of this arrangement is the exposure of the contacts to salt vapor and heat; its main advantage is the lack of expensive shaping of the electrode, ease of replacement, and avoidance of welding. Limited voltage and power adjustments may also be made by changing the immersed depth of the electrodes.
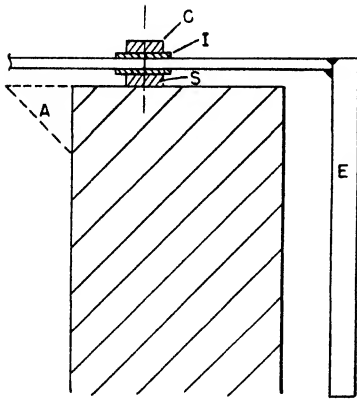
FIG. 89. Electrode arrangement.   FIG. 90. Continuously feeding electrodes.
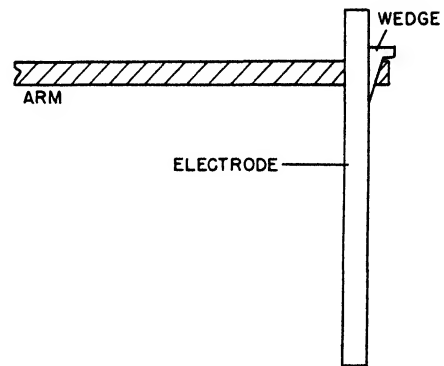
(c) Life Expectancy of Electrodes

The life expectancy of electrodes varies greatly from several weeks (perhaps 15 to 25) for high-speed salt baths (operating at temperatures of 2300 to 2350 F) to perhaps 1 to 1.5 years for well designed case-hardening furnaces. Even for similar applications actual electrode life changes greatly with different electrode designs and even with the same design for various users.

(d) Design

The entire design of electrodes, and salt bath furnaces in general, is empirical. Choice of dimensions rests on several factors:

(1) *Mechanical strength.* Cross section does not determine strength. Weight and carrying area are proportional; an increase in carrying area increases the weight in the same proportion; the stress remains unchanged. Certain minimum dimensions are, however, required to avoid warpage. For this reason no smaller thickness than 1 in., preferably $1\frac{1}{2}$ in., should be used.

(*2*) *Current-carrying capacity.* It is important that the electrodes never act as resistors; the heat generated by the current within the electrode should under all circumstances be negligible compared with the heat generated in the salt proper. This requirement is usually easy to fulfill but becomes a problem in deep furnaces (see page 179).

(*3*) *Voltage drop* Related to the problem of current carrying capacity is that of voltage drop. The voltage at the salt level is necessarily higher than at the bottom end of the electrodes. It is important to keep the difference small, in order to obtain uniform heating (see page 181).

(*4*) *Electrode leads.* The electrode leads connect the electrode proper (immersed in the salt) to the busses. Sometimes the leads form an integral unit with the electrodes (horizontal leg, Fig. 89), sometimes they are detachable (Fig. 90). Their design offers the same problem as the terminals of resistors and the electrodes in arc furnaces (see page 81). Increasing their cross section lowers the resistance and therewith the ohmic losses, but at the same time increases the heat conduction from the bath. The fact that the leads are entirely open accentuates the heat losses. An accurate solution of this problem of dimensions is not yet available. Some designers apply water cooling to the electrode leads in order to improve the contact between leads and busses.

2. Electrical Parts

The electrode leads receive current from the transformer by way of the busses. The latter are usually made of copper. The same design principles apply as discussed in Volume I (page 136) for arc furnaces. However, the bus currents being in the order of magnitude of only $\frac{1}{20}$ of those in arc furnaces, the difficulties are not as great. Interweaving of busses is usually not applied. Busses made of copper are mostly subdivided into several parallel straps.

Transformers have a number of taps, usually not less than five, often many more. The taps are provided on the primary winding. A high power factor on all taps is desirable; this calls for careful distribution of the coils. Tap-changing switches are usually not to be operated under load.

Automatic temperature control calls for permanent immersion of a thermocouple, which is always placed in protective tubes. Tubes are made of steel or various alloys according to temperature and salt applied. Under severe operating conditions frequent inspection is necessary to avoid destruction of the couple proper by penetrating salt or vapor. For high temperatures, radiation type and optical pyrometers which observe the bottom of an immersion tube have been used.

3. Pots

The salt is melted in either ceramic or metallic pots. The main requirements for such pots are resistance against attack by the salts and tightness to avoid leakage of salt. Small pots with round cross section may be cast, but larger metallic pots of rectangular or irregular shapes are usually welded.

For many salts used at temperatures up to 1500 or 1600 F, pots of firebox steel and of commercially pure iron have proved very successful. Since commercially pure iron probably picks up carbon out of carburizing baths in short time, it does not stand up, under attack from the inside, any better than does steel. However pots frequently fail because of oxidation on the outside, and in this respect commercially pure iron is superior to firebox steel.

For higher temperatures, alloy pots are used with considerable success. For most salts the use of alloys with high nickel content is less desirable than alloys with high chromium content. The disadvantage of the latter is the greater difficulty in welding.

Cast pots should of course have well rounded corners and be uniform in thickness. Avoiding sharp corners helps also prolong the life of welded pots. It is desirable to keep the number of welds as low as possible which may be done by cutting as much of the pot as practicable from one sheet (Fig. 91). Welding should be done from inside and outside. Although there is no complete safeguard against leaks, the tightness of the pots should be tested by filling them with oil and letting them stand for a considerable length of time. Pot failure occurs usually by a leak forming after some length of service. As soon as the leak is noticed the current is shut off and frequently at the same time as much of the salt as possible is bailed out. Yet some salt freezes in the pot, and when bad leaks occur salt

BEND ALONG BROKEN LINES

FIG. 91. Plate layout for rectangular pots (bend along broken lines).

escaping to the outside binds with the lining. Lifting the pot out of the furnace then becomes difficult. Attachments to which the hook of the hoist can be fastened will facilitate handling of the pot.

Thickness of pots depends on size and operating temperature. Small pots at low temperatures may be as thin as ½ in. but this is exceptional. A thickness of ¾ to 1¼ in. is more common, and exceptionally thicknesses up to 2 inch are found.

Life expectancy figures are difficult to give.   The life of pots depends not only on design and operating temperature but also to a considerable extent on the method of operation and the salts used.   Rapid temperature changes (that is rapid heating-up, the rate of cooling being limited by the insulation) and the frequency of cooling are among the most important.   Pot lives of 1 to 1½ years at carburizing temperatures have been reported.

Pots which are to be used in externally heated salt or lead baths are usually made integral with a flange to protect liquid dropping into the furnace chamber (see Fig. 156, page 189).

Ceramic pots are made either of individual bricks or of concrete, resulting in a monolithic wall.   Occasionally complete portable non-metallic pots are used.

The nature of the brick to be used depends on salt and temperatures. The danger of reaction between pot and salt, and formation of decarburizing compositions, must be kept in mind.   In any salt bath furnace the dangerous consequences of a leak of the pot must be considered. Much is being said about the self-sealing properties of refractory pots. The underlying idea is the following: if a crack should develop salt will seep out, but will solidify near the outside surface of the pot and consequently seal the leak.   However, liquid salt has a very much higher thermal conductivity than the frozen salt, and consequently the point where the sealing is supposed to occur is easily fed with heat from the still liquid part.   Moreover, if much heat is to be extracted from the liquid stream coming from the leak, the thermal conductivity of the lining must be good.   This in turn means that the wall losses must be high.   Thus well insulated furnaces have poor self-sealing properties, and good self-sealing properties necessitate poor heat insulation.

4. Covers

The greatest part of heat loss from salt bath furnaces occurs by radiation, and to a smaller extent also by convection from the unprotected top of the bath (Table XV, page 174).   Hence it is important to cover the bath as well as possible.   There are two classes of covers: one covers the parts of the salt surface which need not necessarily be accessible.   A cover around the electrodes is an example in point.   The second type covers the space between the electrodes.   This space cannot be utilized, yet contributes to the radiation loss.   It is therefore a good (although too rarely followed) practice to cover this part of the bath semipermanently, the cover to be withdrawn only for changing electrodes, cleaning the pot, etc.   Similar semipermanent covers (Fig. 92) could be used in the corners and in some continuously operated furnaces; then considerable savings would be possible.   Although such great sav-

ings as in the furnace shown here are only rarely possible, the figure indicates the possible reduction in radiating surface. Even thin covers of perhaps $1\frac{1}{2}$ to 2 in. thickness cut down the radiation loss considerably. The design of semipermanent covers is not simple. Usually they rest on many points of the furnace side walls but must hang at least in part free over the bath. If too many metal suspensions reach to the bath level the purpose of the cover is in part defeated.

The covers for batch type baths must be easily removable. They should be so designed that they do not warp under the influence of rapid temperature change (from exposure of the bath to cold air). Basically there are two possible designs: either the cover turns on hinges and thus is moved out of the plane of the bath surface, or it is moved parallel to the bath. The latter is the generally accepted design, except for some cases where the cover is put on the pot loosely and can be taken off by hand. When closed, mechanical covers should be as close as possible to the salt level. The electrodes protruding above the salt level add to the design difficulties. One way to overcome these is to raise the sides of the pot and let the cover slide on a high level; the electrodes are cleaned without difficulty, but the substantial distance of the cover from the salt level to the lid makes the cover ineffective (Fig. 93). In another design the cover in its closed position rests on the pot and, in order to clear the electrodes when moved, is first lifted (Fig. 94).
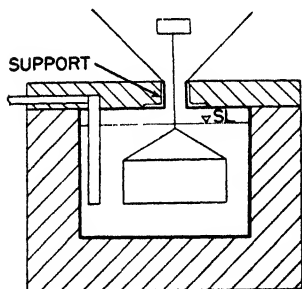
FIG. 92. Part cover for salt-bath furnace. *SL* is the salt level.
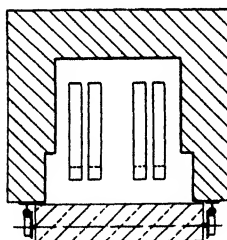
FIG. 93. Cover design for salt-bath furnace.
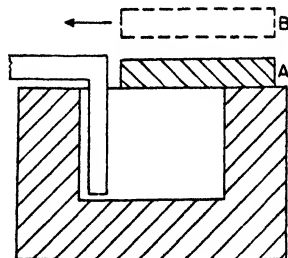
FIG. 94. Cover design for salt-bath furnace in closed position (*A*) and in position for moving cover (*B*).

IV.   FURNACE DESIGN

The previous section referred to furnace parts, and the present one deals with the furnace as a unit. The examples are selected from a large number of designs. Power consumption figures are generally omitted because data available in literature or from trade publications do not have the information necessary to make them definite. For the same

load, for instance, power consumption changes with the degree of uniformity of the charge. Power consumption per unit weight also changes with load density. The field of indirect-heat furnaces (furnaces in which the charge does not form part of the heating circuit; see page 6, Vol. I) is subdivided into three groups: radiation type, convection type, and conduction type, which are treated separately. It should be understood that many of the designs shown under the heading "radiation" furnaces are also being built with minor changes as "convection" furnaces.

A. RADIATION TYPE FURNACES

1. Introduction

The design of radiation type furnaces is different for low-, medium-, and high-temperature furnaces. In low-temperature furnaces and ovens of radiation type, infrared lamps are used increasingly as heat source. Other low-temperature work is done mostly in convection type furnaces, so that low-temperature radiation type furnaces (no fan, no infrared heating) other than infrared are not treated here in detail. The latter are built, to a great extent, like medium-temperature furnaces, except for the fact that the inside wall is metallic. Resistors for such furnaces can be designed with high energy density and are frequently of the frame type (page 79). Thus, under the heading of "low-temperature furnaces" only infrared heating will be discussed. The distinction between medium- and high-temperature furnaces is based on the resistors. Medium-temperature furnaces are built with metallic resistors, high-temperature furnaces with nonmetallic. The distinction is not quite definite because in some instances nonmetallic resistors are used for "medium temperature." Also the recently developed iron-chromium-aluminum alloys are used increasingly in fields of higher temperatures, previously considered an exclusive field for nonmetallic resistors. At the present stage of development the subdivision however holds still so generally that it is maintained here.

Radiation type furnaces are used in many different fields and for almost all materials that have to be heated. Fields of application are therefore listed in the various subchapters (low-, medium-, and high-temperature furnaces).

2. Low-Temperature Ovens and Furnaces

"Infrared heating" consists in exposing for very short times to very high temperatures a body, the surface of which is to be heated to a low temperature only. Hence it may be considered an application to solid bodies of the heating method applied for many years to the singeing of textiles. The nature of the heat source—lamp bulbs, metallic or non-

metallic resistors, radiant burners, etc.—is incidental to the basic condition of rapid heating in short-time exposure.

Infrared heating has its most useful application in heating thin material. In drying (the most important use to date), infrared heating should be applied to drying surface finish such as varnish, not to drying of material to any appreciable depth as in foundry molds and cores, food, etc. In such cases the rapid increase of surface temperature results in a dried layer at the surface which prevents successful transfer of the moisture from deeper layers. Similarly for operations other than drying the best application is for thin materials, such as paper and textiles.

To date, infrared heating has usually been carried out in the open, that is, by exposing the charge to incandescent lamps without enclosure. The recent trend is away from this crude, inefficient design and toward well insulated ovens. The mechanism of heating by infrared is better understood in "open heating," and will therefore be described first. Modifications to account for the enclosure will be added later.

(a) Open Infrared Heating

PRINCIPLES OF INFRARED HEATING

Consider a body exposed to a radiant heat source of high temperature but surrounded by relatively cool air. The flow of energy from the heat source to the surface is broken into two parts: one entering the body and heating it, the other being redispersed from the surface and used to heat the surrounding air atmosphere. It is of interest to note also that this division of the impinging energy occurs in other instances too, as in high-frequency heating in coils (not in closed melting furnaces), in which the energy generated at the surface is consumed in part to heat the interior of the body and in part to raise the temperature of the surroundings (page 263). Another instance of a similar heat flow pattern is encountered in walls of air-conditioned buildings: heat is received on the outside from the sun; part of it is dissipated from the surface and raises the temperature of

FIG. 95. Heat flow pattern in infrared heating: B, begin; E, end; HT, heating time.

the surroundings, while the balance penetrates the wall and is absorbed by the coolant of the air conditioning equipment. The pattern is represented schematically by Figure 95. The width, s, represents the total rate of heat flow being received by the surface. This stream is split into two parts: a, represents the rate of heat flow absorbed by the body; b, the rate of heat loss to the surroundings. As heating progres-

ses the relative magnitude of the two parts changes, *a* decreasing and *b* increasing. At the end of the heating period the entire heat received is lost to the surroundings.

In considering a unit area of surface of the charge, the following items determine the heating process:

time of exposure

rate of energy impinging on the sur-⎫
  face, absorption factor of surface ⎬ determine mainly heat received at surface

thickness, specific heat, density,⎫
  thermal conductivity of stock ⎬ determine mainly heat transmitted into body

temperature of surrounding air,⎫
  boundary conductance of air ⎬ determine mainly heat lost to surroundings

initial temperature of stock

The three streams of energy are interdependent; the notations indicating which variable refers to either stream of energy are only approximate.

Heating conditions have so far been explored only for bodies up to about 0.12-in. thickness, and the following considerations hold for such thin metal. If the stock is thicker, heating of the surface is slowed down until it is no longer reasonable to speak of "short-time exposure." For heavy stock it would be replaced by a fairly long period of medium surface temperatures.

BASIC RELATIONS FOR THIN MATERIAL

Conditions are different for thin and thick material and are very much simpler for the former. Tiller and Garber [52a] developed relations for thin material several years ago at a symposium of the Am. Soc. Mech. Engrs. These conditions have been restated.[52b, c] Moreover, Tiller and Garber developed the relationships for thicker material.[52d] Conditions for thin material will be discussed first, in conjunction with Figure 96.[52a] It is necessary to introduce the idea of a "performance ratio," *P*, which is defined as follows:

$$P = \frac{\text{heat retained by stock}}{\text{radiant heat impinging on surface}}$$

[52a] F. M. Tiller and H. T. Garber, *Ind. Eng. Chem.*, **34**, 773 (1942). See also *Power Sales Manual*, Edison Electric Institute, Section IV, "Infrared Heating."

[52b] P. H. Goodell, "Practical Considerations Relating to the Use of Infrared Heating," Am. Soc. Mech. Engrs. annual meeting, New York, 1946.

[52c] J. B. Carne, "The Role of Convection in Medium Temperature Processing, with Special Reference to Its Influence on the Design of Infra-Ovens," Am. Soc. Mech. Engrs. annual meeting, New York, 1946.

[52d] F. M. Tiller and H. J. Garber, "Theory of Radiant Heating with Incandescent Lamps," Am. Soc. Mech. Engrs. annual meeting, New York, 1946.

It is assumed that all the heat absorbed by the stock is used to raise its temperature; no evaporation or chemical processes liberating or absorbing heat occur. In Figure 96 several items characterizing the process are plotted against heating time for one specific example. First, the energy input to the surface is plotted; the rate of energy being constant (4 w per sq in.), the total energy input is directly proportional to time, and hence a straight line results (Curve 2).

Since 1 w = 3.41 Btu per hr, the energy after flowing for one minute at the rate of 4 w per sq in. equals·

$$\frac{4 \times 3.41 \times 144}{60} = 32.8 \text{ Btu per sq ft}$$

Part of the energy is reradiated or reflected. The absorptivity, defined by the dimensionless ratio of radiant heat absorbed by the stock divided by the impinging radiant heat, is a temperature function. As a simplification, it is considered constant; hence Curve 4, representing "energy reflected," is also a straight line. Actually, as the temperature rises, the absorptivity becomes less and the reflected energy curve will slip downward.

Energy reradiated or reflected from the surface does not contribute toward heating the charge, so the "energy absorbed" line is the difference between the "energy input" and "energy reflected" lines.

Example. For 1.5 min, the accumulated input is 49.2 Btu per sq ft, the accumulated reflected energy is 6.8 Btu per sq ft, and the energy absorbed thus is 49.2 − 6.8 = 42.4 Btu per sq ft.

The explanation could end here, if heating occurred in a vacuum, but the surrounding air is a factor in the heat flow pattern.

The temperature of the air being 150 F, while that of the charge is initially at 80 F, the air contributes initially to the heating. However, when the temperature of the charge reaches 150 F (that is, the temperature of the air), no heat is transferred from the air to the charge; when the temperature of the charge rises further under the influence of the radiant heat, the process is reversed and the air is heated from the surface of the charge, thus decreasing the amount of heat available for raising the charge temperature.

The accumulated energy transferred by convection ("energy gain by convection," first positive and later negative) is given as a separate curve 5.

This curve, showing accumulated values, crosses the zero line at a time when the temperature is well beyond 150 F. In the interval between the 150 F point (0.29 min) and the point where there is zero energy gain by convection (0.70 min), the heat gain by convection, accrued in 0.29 min, is being used to cover the early heat losses.

By subtracting the "energy gain by convection" curve 5 from the "energy absorbed" line 3, the "sensible energy gain" curve 6 is found.

For example, at 1.5 min the "energy gain by convection" is (negatively) 13 Btu per sq ft.   By subtracting this from the 42.4 Btu per sq ft found above as the value for the "energy absorbed line" at 1.5 min, the "sensible energy gain" at 1.5 min is found: 42.4 − 13 = 29.4 Btu per sq ft.

The sensible energy gain is used to raise the temperature of the charge.   Thus the "temperature" curve 1 is established.

Curve 7 shows the performance ratio plotted *vs.* time.   The performance ratio starts with a value higher than 100%.   Under the influence of the convective heat transfer the heat gain of the charge at the start of the process is greater than the energy input by radiation.   As the temperature of the charge increases, and heat losses by convection as well as reflected energy grow, the performance ratio drops.

In the example for 1.5 min heating time, the energy input is 49.2 Btu per sq ft; the two loss items (reflection and convection) are 6.8 and 13 Btu per sq ft respectively; thus the performance ratio is:

$$\frac{49.2 - (6.8 + 13)}{49.2} \times 100 = 60$$

The performance ratio curve shows that, with a heating time of 1.5 min, only 60% of the accumulated energy input (by radiation) is utilized.

INFLUENCE OF VARIABLES

Figure 96 lends itself readily to a study of the different variables.

If the *rate of energy input* is increased, with all other conditions unchanged, the reflected energy increases in the same proportion and hence the absorbed energy increases also in the same proportion.   For a given load the heating time necessarily becomes shorter, and therefore the deduction for convective losses becomes smaller or may even become

FIG. 96.   Operating curves for infrared heating.[52a]

"positive," that is, the charge may receive heat by convection in addition to radiation.

The main limitation to an increase of rate of energy input is the spacing of heaters.   At present 10 w per sq in. is considered the maximum

practical heat density, but values up to 15 w per sq in. may be obtainable. Excessive increase in density results in nonuniform radiation, which is less noticeable in continuous ovens than in batch type ovens.   In continuous ovens each section of the surface is successively exposed to varying radiation patterns, which may at least in part serve to cancel out local non-uniformities.

The *absorptivity of the metal* as defined above includes the "emissivity" factor and a temperature function.   The latter is equal to the difference of the fourth powers of absolute temperatures (degree Rankine = degree Fahrenheit + 460) of the heat source and the charge (see Vol. I, Fig. 9).   Within the proper range of application of "infrared heating" this difference can with reasonable accuracy be considered constant. Hence, for practical purposes the absorptivity depends solely on the emissivity of the heat receiving surface.   If transparent paints are to be dried, then the "heat-receiving surface" is that of the metal.   If the paint is opaque, then its surface is the "heat-receiving surface."   The influence of the paint on the results is illustrated by a test of four paints of similar composition resulting in absorptivity figures as follows: black, 0.86; blue, 0.62; red, 0.59; white, 0.48.   Some manufacturers have changed their paints in order to permit the use of infrared heating.   This is an interesting illustration of a manufacturer adapting his product to the characteristics of heating equipment.

The *air temperature* is of great significance.   First, it is a determining factor in the maximum achievable temperature in infrared heating.   Obviously the temperature of the workpiece cannot rise beyond the point where the entire heat received by radiation equals the heat lost by convection to the surroundings.   Thus the maximum temperature, t_m, can be expressed by:

$$t_m = t_a + (q_r \alpha)/h \tag{18}$$

where t_a denotes air temperature (F), q_r the heat received by radiation (Btu per sq ft, hr), α the absorptivity (dimensionless), and h the boundary conductance (Btu per sq ft, hr, F).   Even more important, the speed of heating to any temperature is increased as the temperature of the surrounding air is increased.

Boundary Conductance.   The boundary conductance is determined mainly by the air velocity.   If the air temperature is below the desired final temperature of the stock, heating of the stock is more rapid, and higher temperatures can be obtained, provided the boundary conductance is low, which implies that the air velocity is low.

Low air velocities are less desirable for removing vapors from the product to be dried.   Obviously an ideal way to reconcile these contradicting needs is to work with high air temperatures.   If the air tempera-

tures are higher than the final temperature of the stock, then the high velocity and high boundary conductance not only are not detrimental but are in fact helpful. High air temperatures may be obtained by applying an external air heater, which need not be operated electrically but can use less expensive energy.

Thickness and Properties of Stock. For a given area of exposure to radiant heat, a certain amount of heat is available for heating the charge (see Curve 6, "sensible energy gain," in Figure 96). Thin stock of low volumetric specific heat (volumetric specific heat = density × specific heat) heats faster for any given amount of sensible energy gain than does thick stock of high volumetric specific heat.

As long as the basic assumption holds that the material is thin enough to permit neglecting temperature differences within the cross section, the thermal conductivity is of no influence on the heating of the stock. However, in many instances the radiation is not uniform at different levels of the oven; in such cases good conducting materials such as copper tend to compensate internally for the unequal receipt of heat.

In batch type ovens, in which at present material is not heated uniformly because of nonuniform radiation, a design might be used where the entire batch is passed in front of the heaters, for example by some kind of stationary walking beam arrangement (see page 65). It is as yet difficult to eliminate hot spots in heat production by infrared; their detrimental effects, however, might be greatly lessened by exposing each part in the batch type oven to various degrees of radiation in successive periods of time by a design as explained.

To determine heating times the methods of calculation applicable to induction heating can be used if the material to be heated by infrared is exposed symmetrically from all sides to the same temperature. For the case in which the material is exposed to infrared radiation on one side only, while the other side is exposed to the oven temperature, Tiller and Garber [52d] have developed useful graphs from which the temperature-time history of the piece can be read.

(b) Closed Ovens

The preceding section deals with infrared heating applied in the open without enclosure. Although until recently the accepted method of application, this procedure is not justified. As in convection type ovens, perhaps even more so, the working space should be enclosed and well insulated.[52] Therefore, it' will be briefly examined how conditions change by using an oven.

By enclosing the working space, the absorptivity will increase and therefore a higher temperature can be reached (Eq. 18) and rates of heating will be higher. Moreover, the air cannot escape unless openings

purposely provided are left open.   Thus the air will more readily heat up and thereby improve conditions.   Also, the air can pick up heat not only at the surface of the charge but on the oven wall as well, increasing still more the speed of heating.

The furnace walls pick up heat slowly, and therefore conditions change during the heating period.   Reradiation decreases as time progresses, because the walls surrounding the charge gradually increase in temperature.   The air temperature does not reach its final value immediately.   In view of this gradual increase it is necessary to use, for the same pieces loaded in the same way, different heating times depending on the time elapsed after starting the oven.

(c) Heat Sources

Infrared heating can be applied by using any of a number of heat sources—electric or gas.   Originally electric incandescent lamp bulbs were applied, the filaments of which operate at approximately 3800 F.   Open ribbon or wire wound resistors, operating not above 2000 or 2100 F, could also be used.   The main advantage of the lamp over the other types is that the heat source is all enclosed, and the glass body is comparatively cold.   Thus, with combustible products from the charge present in the oven the fire hazard is reduced with incandescent lamps.

Two types of incandescent lamps are available: lamps with tungsten filaments and those with carbon filaments.   The latter have higher initial thermal efficiency (by reason of the fact that carbon filament lamps are less efficient light sources).   However, after about 100 hours they are blackened by carbon deposit to such an extent as to make them less efficient than tungsten filament lamps.   The latter are at present available in ratings up to 1000 w.

Except when a reflecting surface is built into the bulb, a separate reflector outside the bulb is necessary to throw all the energy into the load.   The reflector surface should be of a type which will retain its brightness, even under the influence of vapors given off by the charge, and should be readily cleanable.   Aluminum coating on the reflector is preferred at present.   In future developments, it will be well to consider the influence of reflector shapes and sizes on uniformity and output.   Sizes and shapes of reflectors determine the number of reflectors and lamps that can be placed per unit area.   Various shapes for the reflector contours have been tried, but opinions as to the best shape are divided.

Since no coating stands up too well under repeated cleaning, in a more recent development the lamps are put behind sealed lenses.   Refer, for example, to Figure 2 of the article by Tiller and Garber.[52a]   The lens can be readily cleaned without danger to the bulb, and the fixture for the bulb can be placed outside the oven proper.

3. Medium-Temperature Furnaces (with Metallic Resistors)

(a) Applications

Of all resistor furnaces the greatest number is used in the medium temperature field. Some of their varied applications are listed:

METALS

Heating for hardening
Carburizing
Annealing (bright, clean, or common) of steel and ferrous metals
Malleabilization
Normalizing
General heat treating
Annealing (bright, clean, or common) and heating for pressing of copper and its alloys
Melting, annealing, and age hardening of aluminum, magnesium and light alloys
Melting lead, tin, zinc, and similar metals
Brazing and soldering ferrous and nonferrous metals
Vitreous enameling

CERAMICS AND GLASS

Glass lehrs
Decorating kilns for china and earthenware

CHEMICALS

Cracking of gases
Coke production $\Big\}$ in experimental use only
Oil stills

MISCELLANEOUS

Cremation furnaces (not discussed in this text; see, for example, Graenzer[53] and Weiss[53]).

Most of these processes can be carried out in continuous or in batch type furnaces.

(b) Batch Type Furnaces

These furnaces may be conveniently grouped into furnaces with vertical and with horizontal working openings.

VERTICAL WORKING OPENING

This group comprises the common type of simple box furnaces (see Figure 97). In many instances rear wall, door, and roof are not covered by resistors. The hearth plate protects the bottom resistors against dirt and oxides from the charge and can be designed with a certain minimum spacing between charge and side resistors. Figure 98 shows a cast hearth plate with heavy side flanges which prevent putting the load too close to the side resistors.

It is difficult to produce uniform material in simple box type furnaces. This of course is true, independent of the source of heat: electric, gas, oil, etc. If the hearth is heated from underneath and material rests on the hearth plate, the bottom of the load (in contact with the plate)

[53] Bull. tech. Suisse romande, 65, 21 (1939). K. Weiss, Gesundh. Ing., 60, 159 (1937). R. Graenzer, Elektrowärme, 8, 148 (1938).

Adjustable Door Clevises

Terminal Guard — Similarly on Rear Head

Flexible Leads to Door Heating Elements

All Connections At Back of Furnace

Steel Front Plate Rigidly Reinforced

Adjustable Door Jambs

Heating Element In Rear Wall — Easily Removed

Door Operating Lever With Ample Mechanical Advantage

Fire Brick Vestibule

Cast Alloy Hearth Plate

Door Seals Tight — Without Sand Seal

Wide Door Lap — No Through Metal

Heating Elements In Hearth — Easily Removed

Self Aligning Ball Bearings

Sheet Steel Door — With Welded Reinforcements

Heating Elements in Door — Easily Removed

Adjustable Counter weight Balances Door

Heating Elements In Arch — Easily Removed

Heavy Steel Shell Rigidly Reinforced

High Temperature Insulating Brick

Medium Temperature Insulating Slabs

Low Temperature Insulating Slabs

Heating Elements in Side Walls — Easily Removed

I beam Supports

FIG. 97. Batch type furnace with vertical working opening
(Courtesy *Hevi Duty Electric Company.*)

absorbs heat very rapidly, and, after having received all available heat from the plate, lags in temperature behind the top. Thus the bottom will at first heat more rapidly, later more slowly, than other surfaces of the charge exposed to the heat. If the bottom is not heated, the heat losses from the bottom must pass, at least in part, through the charge, which will now be again nonuniform, the top and all sides heating more rapidly than the bottom. A reasonable degree of uniformity, all other conditions being fulfilled, may be expected if a single piece is placed on supports, thus being practically suspended in the center of the furnace chamber.

FIG. 98. Cast hearth plate.

If a box type furnace of large size is loaded with more than one piece or with a piece of irregular shape, only limited uniformity of the charge
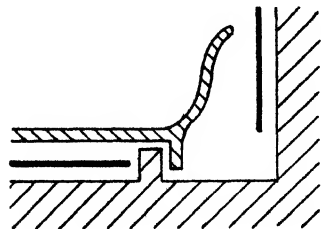
can be obtained.   Take, for example, the case of several piles of loco-
motive tires arranged on the bottom of a furnace, as shown in Figure 99.
Radiation along arrows *a* and *b*, respectively, differs, and therefore the
parts of the charge located on axis *A–A* are in the "heat shade."   Better
uniformity is obtained if the furnace bottom is provided with rotating
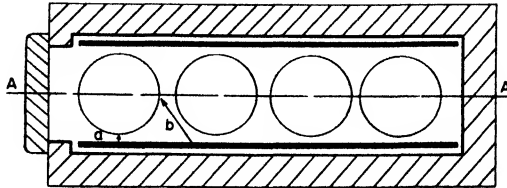
FIG. 99.   Long furnace with turn tables.

disks, each disk being large enough to carry one pile of tires.   During
the heating, the disks with the charge rotate slowly, thus exposing all
parts of the circumference successively to all directions of radiation
(arrows *a* and *b*).

A modification of the box type furnace is the car bottom furnace
(Fig. 59).   To prevent infiltration of air, rather elaborate seals are
provided:

On the sides of the car, channels filled with sand or sometimes with oil of high
boiling point are provided, into which reach blades connected to the furnace
body.   Because of relative movement of car and furnace body, either the
blades must be collapsible to permit withdrawal of the car, or the channel must
be open at the end; in the latter case, of course oil cannot be used as sealing
material, and sand must be replenished each time the car has been removed
from the furnace.   The rear seal can be in the form of a collapsible trough, or
of two fairly elastic surfaces (asbestos cushions, for example), being pressed
against each other.   The front seal can be conveniently made by a sand or oil
seal of door against car.

Practically no attempt at sealing, however, can shut off all air in the
corners.

Car bottom furnaces are frequently used in annealing and stress-
relieving castings and welded structures, in annealing tubes, rods, etc.

Uniformity conditions with respect to the charge are in most in-
stances poor; they are improved somewhat by providing supports to
separate the charge from the bottom (Fig. 100) and also by providing
some kind of shelves for the load.   The shelves must be spaced sufficiently
apart to permit heat to radiate into the load placed on the shelves.   The
width of the car is thus limited.   If the width is great the spacing of the
shelves would have to be excessive in order to guarantee a reasonable
amount of uniformity of exposure (Fig. 101).
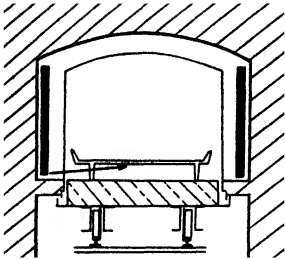
FIG. 100. Car bottom furnace with support. Charge is spaced from the bottom, so that it can receive heat from the sides by radiation, and is not cooled from the bottom.
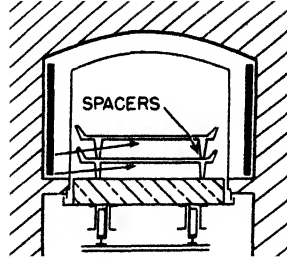
FIG. 101. Space limitations for side radiation. If width of furnace is too large, radiation cannot reach center of charge.

Car bottom furnaces, if piled with small castings or similar objects, are poor in uniformity. Even in the best designed car bottom furnace, having perfect temperature distribution in the empty space and perfect temperature control, the outside pieces receive heat on the side exposed to the resistors relatively quickly, whereas the temperature of their parts in the "heat shade" lag considerably. Pieces on the inside undergo the same cycle: outside surfaces receive heat earlier than do the surfaces facing the inside. In addition the inside piece is heated later than the outside piece, that is, only after the inside surface of the outside piece has reached a temperature sufficiently high to yield an appreciable amount of radiation. Therefore the outer piece is exposed to heat a longer time than the inside piece. The outside piece, receiving heat directly from the resistor, heats at a more rapid rate than does the inside piece. Thus all three fundamental conditions of uniformity previously mentioned are poor. Figure 102 shows schematically three castings (a, b, c) loaded in a furnace provided with resistors on the sidewalls. The three pieces are separated by air spaces, which even if small, always represent a thermal resistance. The resulting temperature-time curves are shown in the right part of the figure. If, as in the present example, the pieces have the same height as the furnace, replacing the side heat by heating top and car bottom would be sufficient. However, the drawing is a simplification because in annealing castings, frequently small castings are loaded on the car bottom. The size and shape of the small pieces cause discontinuity in the vertical direction also and therefore similar lags between the top (and/or) bottom and center.

HORIZONTAL WORKING OPENING

Furnaces of this type have either a removable top or a removable bottom. Furnaces with removable top are commonly called pit furnaces,

if used for heat treating, and pot furnaces if used with a pot for melting. Pit furnaces are made with circular or rectangular cross section and are often entirely or largely below shop level, in the ground. This type of furnace is suited for heating long objects which for uniformity are suspended while heating. For such a use the furnace walls must be strong enough to support the weight of the charge, transmitted to them by suspension tools; or a split cover must be provided and the pieces suspended from the outside. Floor space requirements are limited because generally the space above the walls can be used as passage. Pit furnaces
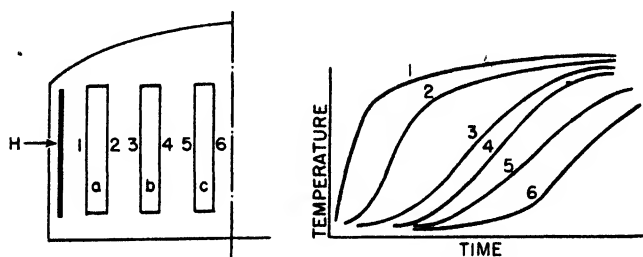
Fig. 102. Schematic temperature rise in castings. (Left, arrangement of castings. Right, temperature curve. Figures on curves refer to surface of castings.)

have relatively low steady-state heat losses because the soil surrounding the furnace acts as insulation, but for the same reason the heat storage is comparatively high. Pit furnaces are often recommended for charges which must cool slowly, but their natural cooling cycle is frequently too long.

Small furnaces with removable covers are made transportable and are used above shop level (page 157).

Pot furnaces for melting low-melting metals, such as babbit, are built in a way similar to pit furnaces. In the pit a metal pot is inserted, with a pouring spout extending either above the sidewall, or more frequently, penetrating the latter. Such furnaces may be tiltable, either in nose tilt (page 100, Vol. I) or around their center of gravity. In some instances melting furnaces without a spout have been built. The charge is withdrawn by ladling or through a bottom valve.

Another furnace with a horizontal working opening is the elevator type (Fig. 103). The furnace body, supported by columns, is located well above the shop floor. To load or unload, the bottom of the furnace is lowered. In small elevator type furnaces the lowering is accomplished by hand-operated crank; in large furnaces the bottom is operated hydraulically, pneumatically, or electrically. Usually, the bottom is equipped with wheels and can be moved away from under the furnace. If loading

and unloading takes much time, such furnaces can be operated with two or more cars, *e. g.*, one being on a loading station, the second one in the furnace, and the third cooling with a charge.
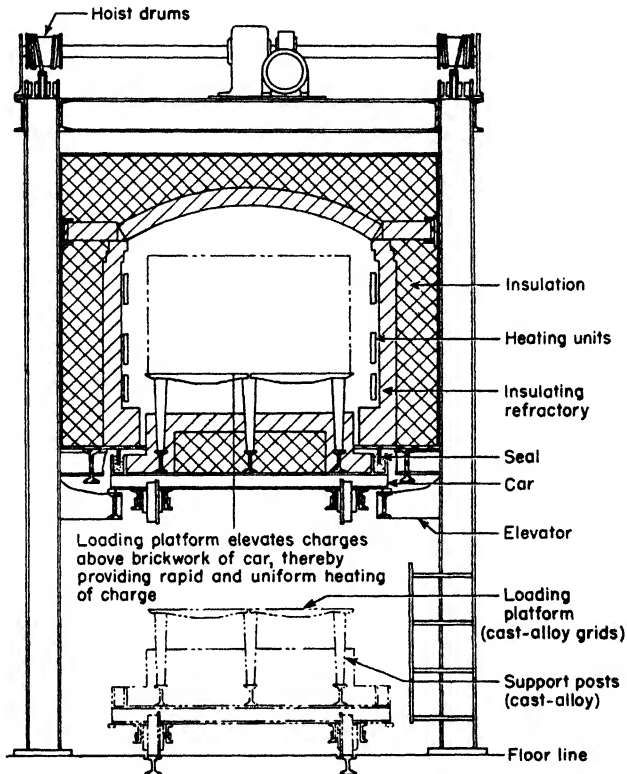
Fig. 103.   Elevator type furnace.
(Courtesy *General Electric Company.*)

Elevator type furnaces are easier to seal and have therefore a slightly better space uniformity of the empty furnace.   However, in one of their main applications—annealing of piles of castings—the uniformity of the charge is as limited as in car bottom furnaces.

Instead of lowering the bottom of the furnace, it is possible to use the inverse method, keeping the bottom in place and removing the top. Such design is known as bell type furnaces, used mainly for annealing. Figure 104 shows a cross section through such a furnace.   Several loading bases may be served by one bell.   At the end of the heating period the bell is withdrawn from the base; without losing the heat stored in the bell, the latter is put over another base on which the next load is pre-

pared. The first charge cools on the base. To prevent oxidation during cooling, a cover is usually placed over the charge. If cooling should be very slow, an insulated bell type cover without heating elements is used, alone or in addition to the retorts. Depending on the necessary degree of brightness, temperatures used, and material, the retort may possibly
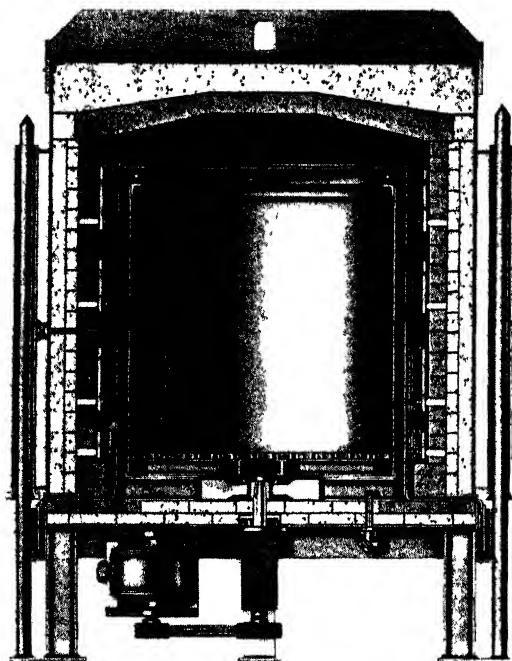
FIG. 104. Cross section through bell type furnace.

be slipped over the charge only after heating, or it may have to be present during the heating process. Similarly, protective gas may be used during heating and cooling. A recirculating fan may insure fairly even distribution of the atmosphere. For large coils or other parts filling the entire cross section of the furnace and possessing an opening in the center, heating within a given length of time can be made more uniform by use of a center heater.

Various arrangements of bell type furnaces are shown schematically in Figure 105.

Bell type furnaces are used extensively for heating steel sheets in stacks. If the chambers are heated from the long sides only, heating can be very uniform. If heating is at the same time done from the short sides

and possibly from the top or bottom, it would have to be effected across the minute air spaces and would become nonuniform.

Heating solid rings—such as locomotive tires—is another example of a legitimate and proper use of round bell type furnaces, where the circumference can receive heat uniformly. The common practice, however, of
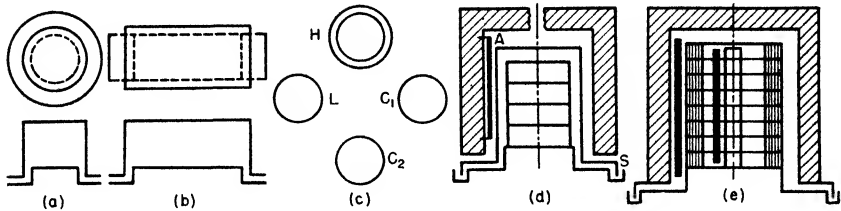
FIG. 105. Layout for bell type furnaces: (a) round, (b) rectangular, (c) four-position type—H is heating position, C_1, C_2 cooling positions 1 and 2, L loading and unloading, (d) left, heated bell; right, cooling bell not heated, (e) furnace with center heater (left heated bell, right cooling bell).

piling many coils on top of each other and heating from the circumference requires long heating times, as does the heating of small coils, none of which covers the entire horizontal cross section. If the time is long enough to produce uniform final temperatures, then the furnace is often not economical; in addition, the rates of heating and the time during which various parts (e. g., outside and inside layer) have been exposed to elevated temperatures are different.[12]

SPECIAL FURNACES

From the many special designs of stationary furnaces only a few can be mentioned.

Protective Atmosphere Furnaces. The design of stationary furnaces with protective atmosphere differs but little from that for common furnaces operated without protective atmosphere. The main change is in the gas-tight shell. Sometimes a small gas producer is connected directly to the furnace. To avoid inrush of cold air when the door is opened, a slot in the door sill will effect the blowing of an increased gas stream across the opening when the door is lifted.

Hardening Furnace with Automatic Indicators.—*Vapocarb Hump Method.* To obtain proper hardness, steel should be quenched above the transformation point. The transformation point or "critical" is characterized by an endothermic reaction, so that the temperature rise is interrupted when the steel goes through the transformation. By recording the temperature on a chart of sufficient size, the "hump" in the temperature curve caused by the transformation can be detected.

The furnace is equipped with two thermocouples: one placed near the heater, the other in contact with the workpiece and through the workpiece protected as much as possible from direct radiation. The rate of energy input is controlled by the difference between the temperatures measured by these two couples. A carbonaceous atmosphere prevents decarburization and oxidation. Proper rate of heating is determined experimentally for any given piece and shape. If, in production, all pieces of the same kind are placed in the furnace in the same way, duplication of good results is safeguarded.

The resistors are of the embedded type (Fig. 67, page 79) and are surrounded by insulating material. The muffle forming the furnace wall rests on a base of insulating bricks, and a top layer of bricks covers the muffle. A cover either lifting around a horizontal axis or swinging out around a vertical axis closes the workroom and should be sealed against the top plate.

Wild-Barfield Type. The Wild-Barfield furnace utilizes another characteristic change taking place at the transformation point: the loss of the magnetic permeability of the charge. The working chamber is heated by a resistor surrounding a muffle and serving not only as heating unit but also as primary coil. This primary coil is in magnetic coupling with an indicating secondary coil, connected to an indicating instrument. When steel or any other magnetic material is put into the furnace, the magnetic coupling improves, causing an appreciable current in the secondary coil The current is measured by the instrument. When the steel reaches its recalescence point, the current on the meter drops to zero. After a predetermined waiting period the material may be quenched.

The furnace works without automatic temperature control and has the same limitations as the Hump furnace: if several pieces are heated simultaneously, transformation may not occur in all pieces at the same time, and consequently the indication can be blurred.

Ugine-Infra. In this furnace of French design a coil surrounds a magnetic muffle which becomes diamagnetic at a certain temperature. Therefore the muffle cannot reach temperatures beyond the transformation point. By proper selection of the muffle material the steel can be protected against overheating.

Vitreous Enameling Furnace. Vitreous enameling is carried out by spraying the material with, or dipping it in, enamel, drying the coating, and then fusing it on. The fusing consists actually in bringing the coating to a quick melt and withdrawing the piece from the furnace before the coating can flow. From this description it becomes clear that thermal uniformity is essential. If one part of the load reaches the melting point of the coating before the other, then the coating has time to melt and flow in this part before other areas are sufficiently hot to soften the

coating. Therefore such batch type furnaces are loaded more lightly than most others. Only one or two layers of material are charged, so that no parts of the charge are in the "heat shade." The charge, being very delicate, is located on loading racks, which are introduced into the furnace by means of forks, manually or mechanically operated (Fig. 106). Important features are: light rack (racks are dead weight, which in view of the open manner of loading become quite important for economy and speed of heating); few but secure supporting contacts between racks and
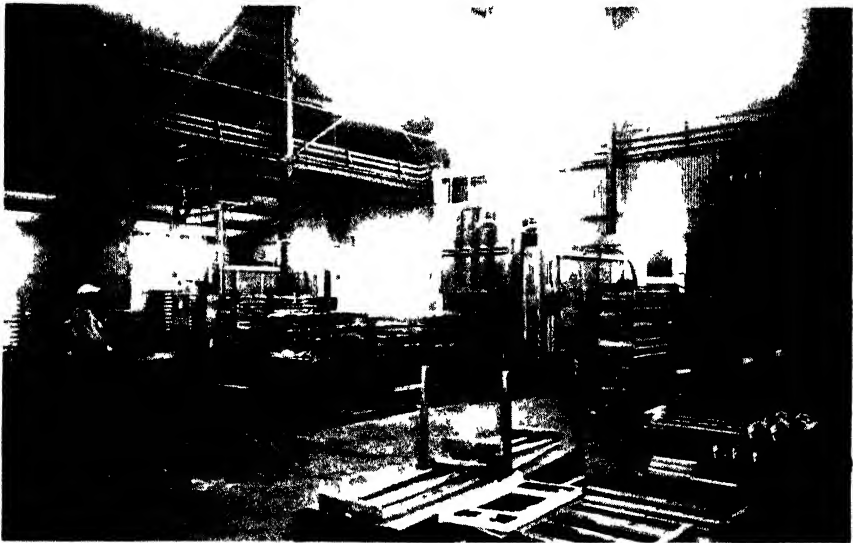
Fig 106   Vitreous enameling furnace.   (Courtesy *General Electric Company*.)

load; rapid movement of the rack—otherwise the parts entering the furnace first would have a materially different exposure time from those entering last; rapid door movement for similar reasons.

Reverbatory Type Melting Furnace. For low-melting metals, such as aluminum, zinc, etc., reverbatory type furnaces may be used. Resistors are placed in the roof and radiate heat into the batch of metal. As the top layer of metal melts, it drops down between the cavities of the lower layers, gradually filling them out. When the batch is melted, the furnace is emptied by tilting or tapping. Another method of operation provides for the continued presence of molten metal in the furnace; at the end of the batch a pool of metal is retained. Because of intimate contact between the cold metal and the liquid pool, rapid melting results.

The low emissivity of aluminum and zinc limit the amount of heat that can be transferred, and therewith the output of the furnace to ap-

proximately 0.88 lb per hr, sq ft of bath surface, independent of the depth of the bath.   Therefore such furnaces are made rather shallow—approximately 5 in. deep.   Power consumption in continuous operation is approximately 0.2 kwhr per lb.

REVIEW OF CALCULATION METHOD

The design of such furnaces should be based on the selection of heating time necessary to obtain the desired uniformity of final temperatures and rates of heating.   Heating time depends on the arrangement of the material in the furnace and determines shape, size, and number of furnaces required for a given output.   The total useful heat per charge and the mean rate of useful heat absorption can now be calculated   Next the heat losses applying to the proposed type of service (continuous or intermittent) are found.   Rate of heat loss and rate of useful energy together determine the connected load, which in turn permits calculation of the resistors

(c) Continuous Furnaces

TWO-DOOR FURNACES

The simplest way of obtaining a continuous flow of work through a furnace is the use of a two-door box type furnace.   Work is entered from one end, moved through the furnace, and discharged from the other end
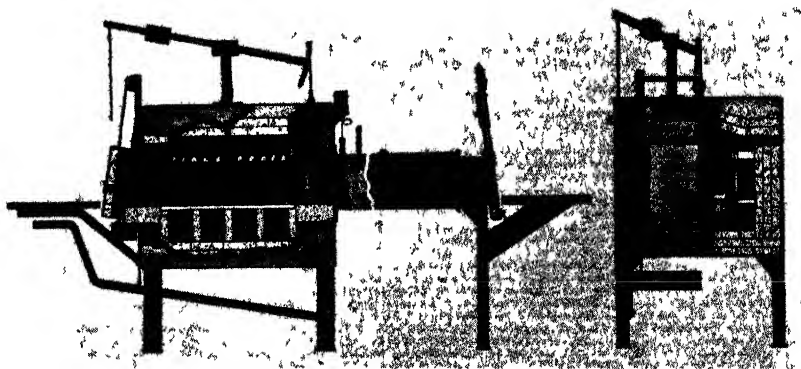
FIG 107.   Brazing furnace with two doors   (Courtesy *Westinghouse Electric and Manufacturing Company.*)

As an example, Figure 107 shows a brazing furnace with two doors, one in the furnace proper and one at the exit of a cooling chamber built integrally with the furnace and permitting the charge to cool in appropriate atmosphere.   To obtain complete cooling, the time allotted is three

times as long as that for heating. Operating temperatures up to 2050 F can be reached in this furnace.

CONTINUOUS STRAND ANNEALING

For wire and strip, continuous strand annealing is the best method of obtaining uniform heating and cooling. For brass strip, strand annealing has been accepted practice in Europe, the greater part of brass strip having been produced in continuous furnaces.[54] Figure 108 shows such a furnace arrangement. The strip is continuously pulled through the furnace, pickling tank, wash tank, and drying oven, and is then coiled up again automatically.
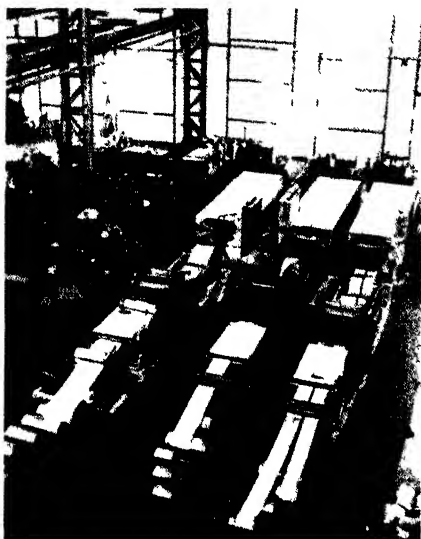
FIG. 108. Continuous strand annealing of strips. (Courtesy *Otto Junker*.)

Because of the uniform heat transfer at a high rate, heating times can be extremely short: for brass, (0.01-in. thick) 60% Cu, 40% Zn, of the order of magnitude of 1.5 to 2.5 min. The strip sags in the furnace in the form of a catenary. Because of the short heating times, the power consumption is low, notwithstanding the poor volumetric utilization: a furnace chamber with a maximum width of 2 ft 6 in. and a maximum height of 8 in. takes strip of only 2 ft width. The furnace chamber is of elliptic cross section. A typical power consumption is 0.038 kwhr per lb.

Copper strip is heated in a similar way, the furnace often being provided with a water seal. The hot strip entering the water evaporates the latter and inasmuch as the retort containing the copper extends into the water, the vapor fills the retort and thus forms a protective atmosphere.

Whereas continuous annealing of brass and copper strip is only slowly, though steadily, being introduced into the United States, this country pioneered in the development of continuous strip annealing of steel—a development not yet completed. Steel wire is pulled through furnaces continuously in the so-called patenting process, in which the wire after being heated to a temperature of 1600 F is quenched in a lead

[54] O. Junker, *Z. Metallkunde*, **23**, 124, 158 (1931); **24**, 162, 301 (1932); **25**, 45 (1933); *Stahl u. Eisen*, **55**, 1167 (1935). G. Hilgenstock, *Elektrowärme*, **4**, 174 (1934).

bath at approximately 750 F. Also, thin bronze wires of fine gage (0.008″) are successfully strand annealed. Frequently, though not always, each wire is led through a separate tube; otherwise the strands pass unprotected through the heating chamber. Figure 109 is a schematic view of this type of muffle arrangement.
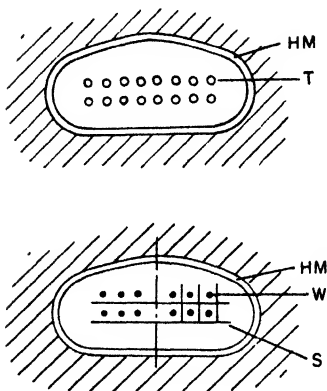
FIG. 109. Muffle arrangements for continuous wire heating: HM, heated muffle; W, wire; T, tubes for passing wire; S, support.

ROLLER-HEARTH FURNACE

In roller-hearth furnaces the charge is sometimes put on the rollers directly, and sometimes in pans, trays, or containers. To secure more uniform heating, top and bottom heat should be applied. The bottom heaters offer some design difficulties because of the danger of parts or dirt falling between the rolls on the heaters. Light hearth plates may be applied to protect bottom heaters; for the latter a design which permits changing of burnt-out units without cooling the furnace is desirable. Another method of avoiding the danger of dirt damaging the bottom resistors, is to provide a rather deep chamber below the rolls and to heat the lower chamber by resistors on the sidewall. Figure 110 shows a schematic cross section of such a furnace. Roller-hearth furnaces are limited in width because of the stress on the rollers. Furnaces up to 4 ft useful width are in successful operation. The length of roller-hearth furnaces, however, is practically unlimited, because more rolls can always be added, and all rolls are power driven and thus their movement is synchronized.

ROTARY-HEARTH FURNACE

While in the roller-hearth furnace the charge is transported in addition to being heated (the exit and entrance are separated by the length of the furnace) the rotary-

FIG. 110. Roller-hearth furnace.

hearth furnace is characterized by the immediate proximity of loading and unloading positions. Thus, from the viewpoint of labor economy, rotary-hearth furnaces have merit for the limited output of not too small individual pieces. One operator can then handle charging and discharging. The rotary-hearth is built up of insulating brickwork,

so that the supporting table and the rotating mechanism are definitely cold. This type of furnace can therefore carry heavy loads—even at high temperatures. Furnaces have been built measuring to 20 ft mean diameter of the hearth. In large furnaces it is possible successfully to subdivide the total path of the charge into individual sections, exposed to different temperatures, and separately controlled. In smaller furnaces individual zones would mutually influence each other.

The width of the hearth and the height above it are limited by the requirements of temperature uniformity in heating. Load placed directly on a nonheated hearth of a rotary hearth furnace must transfer heat to cover the bottom losses and therefore would heat nonuniformly. It is good practice to lift the charge off the hearth surface so that the bottom of the charge can receive heat from side heaters. Conditions in this respect are similar to those in car bottom furnaces (see Figure 100, page 129). Figure 52 (page 67) shows a rotary-hearth furnace. Heating elements are usually placed on the outside and inside periphery and sometimes on the roof but only seldom in the rotating hearth; the latter would require current supply by sliprings.

ROTARY-DRUM FURNACE

The charge in a rotary-drum furnace (Fig. 111) is heated through the wall of the drum. The wall receives heat by radiation from the resistors surrounding the drum and transmits the heat by conduction and radiation to the charge. Drums are frequently equipped with an internal thread, to enforce movement of the charge. Drums without thread are

FURNACE ASSEMBLY   DRIVE UNIT   COOLING DRUM ASSEMBLY   DISCHARGE
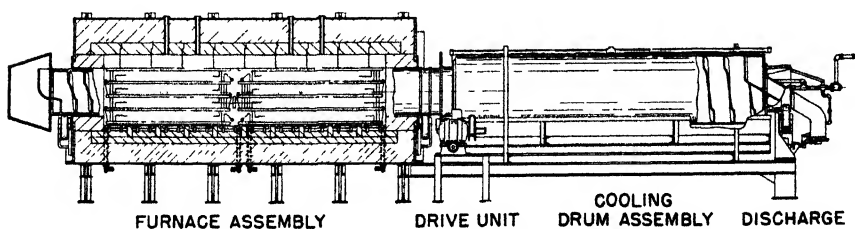
FIG. 111. Rotary-drum furnace. (Courtesy *American Electric Furnace Company*.)

put on an incline to move the charge; drums with thread are sometimes arranged similarly to help the movement. The purpose of the drum movement is to bring continuously different parts of the charge in contact with the hot wall of the drum; as any particle of the charge rises on the wall of the drum, it tumbles and comes to rest on the top of the charge rather than again at the drum wall. Since, frequently, this tumbling is not achieved and the charge slides between the threads, one of the main

purposes of the drum furnace is lost.   Tumbling is aided by putting stops between the threads; the stops prevent sliding, forcing the charge to tumble.

If tumbling occurs, heat is transferred to any particle alternately by one of three means: by conduction through contact with the drum wall; through radiation from the top of the drum, when the piece or particle rests on top of the mass; and through heat exchange with other particles of the charge during such periods when it is in the inside of the mass, neither in contact with the drum nor exposed to the surface.   By continuously changing position and thereby the mode of heating, a better uniformity is achieved for any given heating time than if the charge were heated in a furnace (batch or continuous) of the same length as the drum and with the charge in a layer of such thickness as to hold the same volume of charge as the rotary-drum furnace.

If tumbling does not occur and the charge does slide, heating occurs through the thickness of the layer of the charge, and uniformity considerations are the same as those explained on pages 3–15.

The diameter of the drum and the nature of the work determine what part of the drum is covered by the charge.

In Figure 111 the furnace is connected with a cooling drum, cooled on the outside by a water spray from the top and by a water tank into which it is dipped at the bottom.   Thus a progressive cooling of the charge is achieved; the unit serves annealing purposes.   By omitting the cooling drum, the rotary-drum furnace can be used for heating, hardening, or preheating for punching or similar forming operations.

The mechanical limitations of the drum and the necessity of heating through it restrict this type of furnace to a charge temperature of approximately 1500 to 1600 F.

CONVEYOR FURNACE

Conveyor furnaces lend themselves to the continuous heating of not too heavy material.   They are relatively slightly limited in width but definitely limited in length, particularly with increasing temperatures. At the loading end the conveyor extends out of the furnace chamber, thus enabling the operator to distribute the charge on the conveyor with proper regard to uniformity requirements.   Figure 112 shows an example of such a furnace used for hardening.

In this case the conveyor turns in a discharge compartment, where the parts are dropped directly into the quenching tank.   The latter is then conveniently provided with another conveyor, which carries the parts through the quench bath and delivers them at the top.   In some installations the charge is

then carried through a tempering oven by a quench conveyor or another belt on which the charge is transferred automatically. Thus it is possible to deliver the charge ready for further operations; by convenient arrangement of the conveyor system this delivery can be made at any place in the shop.
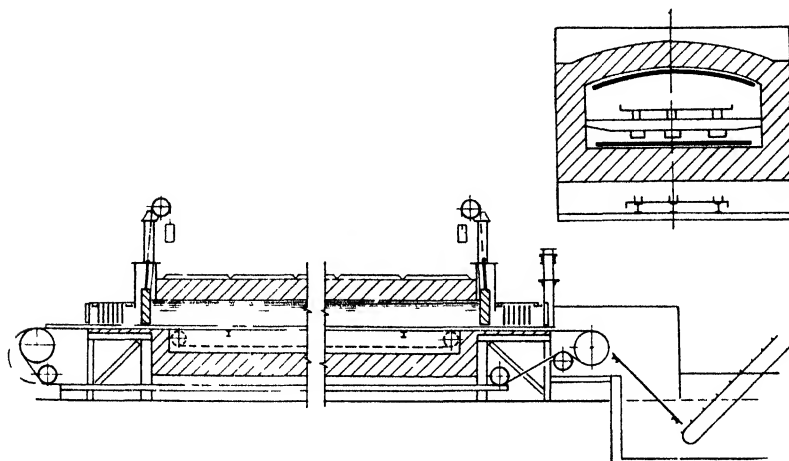
Fig 112. Conveyor type furnace for hardening.
(Courtesy *Intercontinental Engineers, Inc.*)

For annealing purposes the conveyor usually must carry the charge through a cooling chamber; in such instances separate conveyors for the two chambers, as shown in Figure 53, are desirable to avoid continuous heating and cooling of the furnace conveyor. Such cyclic heating and cooling is detrimental to the life of the chain as well as to heat economy. If the parts are very thin, transfer to a separate cooling conveyor may cause a nonpermissible quenching effect through contact. Then the transfer is either avoided or made at a point of somewhat lower temperature, where it is no longer dangerous. Conveyor furnaces can be operated with protective atmosphere for bright annealing, hardening, etc. The openings for the chain cannot, of course, be sealed, and hence cause increased gas consumption.

In Figure 113, another illustration of a conveyor furnace, the conveyor is located above and outside the furnace, and the charge (material to be vitreous enameled) is suspended from light-weight burning tools. The tools are fastened to the conveyor through a slot in the furnace top, the slot being sealed by slide plates. The furnace has one elevated horizontal part and one inclined unheated chamber which serves as heat exchanger between outgoing hot ware and incoming cold material. The heating chamber is closed at the far end, where the conveyor turns; thus

the travel of the charge is in the shape of a U.   A typical furnace of this kind has a total path length of the charge in the furnace of 54 ft of which 14 ft are in the heating chamber.   With a connected load of 450 kw the power consumption is approximately 0.21 kwhr per lb for a useful charge of 1500 lb per hr.
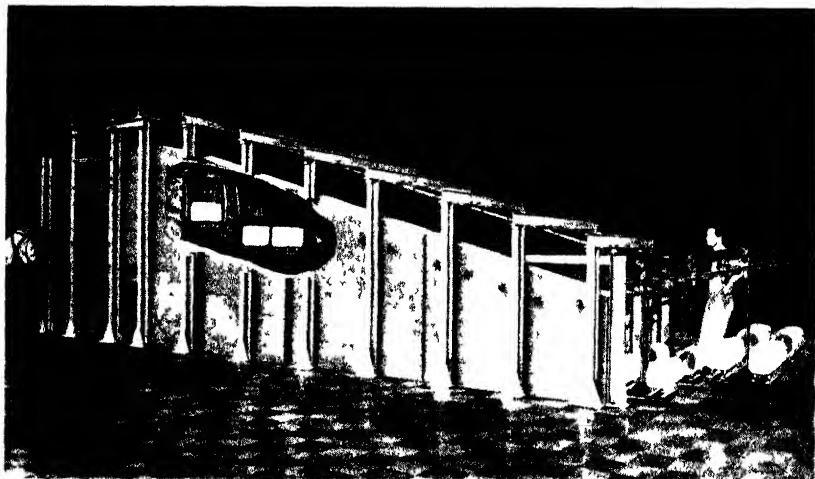
FIG 113   Continuous vitreous enameling furnace with overhead conveyor.
(Courtesy *General Electric Company*)

REVIEW OF CALCULATING METHOD

The calculation for continuous furnaces is based on the same principles as that for batch type furnaces (page 136).   However, some special problems arise in continuous furnaces, because the assumption made in determining the heating time in batch type furnaces no longer holds: the furnace temperature is not equal at different parts of the furnace.   Rather it changes with position, and the charge therefore is exposed to various temperatures as it progresses through the furnace.

To make calculations for continuous furnaces, the furnace should be considered as divided into a number of sections.   In each section the temperature is considered to be constant.   Thus the heating is effected by exposing the charge in consecutive steps to different constant furnace temperatures.   The temperature rise in the load in such a furnace can be determined either by a graphic method, or by the electric analogy method (see Vol. I, page 31).   In most instances both methods are out of question in commercial practice.   Then, in first approximation the heating time can be found by using the method for batch type furnaces

and assigning the furnace temperature obtained from the calculation to the end zone of the continuous furnace.

Next the length of the furnace is determined. In calculating the heating time a certain arrangement of the charge on the hearth must be assumed (e. g., one or two pieces, one on top of the other). From this the weight, w_s, per unit hearth area (lb per sq ft) follows. The speed of transportation, v, is obtained from the desired output, o (lb per hr), the width of the furnace, D_f, and from w_s:

$$v = o \ w_s D_f \qquad (19)$$

Then the length of the furnace, L_f, is found from speed v and heating time θ:

$$L_f = v\theta \qquad (20)$$

The connected load can be estimated by adding calculated heat losses to the useful heat. Due consideration should be given to possible heat absorption by "dead weight" in the transporting mechanism, e. g., a conveyor. The connected load is determined and is subdivided; each zone needs a different rate of energy input, decreasing from a relatively high value next to the entrance to a low value near the exit. The subdivision can be determined as follows: Based on the assumption of a constant furnace temperature equal to that in the end zone, the rise of the surface temperature as function of time of the charge can be found from Figures 5 through 12 (pages 3 to 17). The boundary conductance, h, (see page 5) is plotted against time. If heat transfer is by radiation only, the values of h can be found step by step from Figure 9 in Volume I for the various zones of the furnace. For convection furnaces, h is found from Figure 19 (page 24) and Equations (7) and (8). Surface temperature rise, as well as h values, can be assigned to furnace positions by using Equation (20). By multiplying (for each position) the value of h by the temperature difference (furnace temperature minus surface temperature), the useful heat for the section may be found. After adding the heat losses for the zone and a safety factor for voltage fluctuations, the connected load for the zone may be finally established. Then the resistors are calculated. If it should be found that the resistors cannot be placed in any one zone, then the heating must be slowed down, the furnace be made longer, and the calculation repeated.

Example. Assume that steel slabs, $2L_H = 5$ in. thick, 1.5 ft wide, and 3 ft long, are to be heated at a rate of 7200 lb per hr, and that the slabs will not be piled one on top of the other, but heated evenly and uniformly from top and bottom. In the calculation it is assumed that they receive no heat from the side. The slabs are to be heated to a surface temperature of 1600 F and a center temperature of 1580 F. The thermal properties of the steel in question are: conductivity $k = 18.1$ Btu per ft, hr, F; density $\rho = 480$ lb per cu ft;

specific heat $c = 0.128$ Btu per lb, F; emissivity $\epsilon = 0.79$. Estimate h for radiation. Because of rapid temperature increase of the surface take Ξ for $2/3 \times 1600 \sim 1200$ F and a furnace temperature of 1640 F. $\Xi = 275$ (from Fig. 9, Vol. I). Hence:

$$h = 0.173 \times 275 \times 0.79 = 37.5$$

$$m = \frac{18.1 \times 12}{37.5 \times 2.5} = 2.32$$

$$u = \frac{1600 - 1580}{1600 - 70} = 0.0131$$

From Figure 5 we find for the value of $u = 0.0131$ and $m = 2.32$ by interpolation, $X = 8.4$ and with:

$$L_H^2/a = 6.25/(144 \times 0.295) = 0.147$$

the necessary heating time, θ, becomes:

$$\theta = 8.4 \times 0.147 = 1.24 \text{ hr}$$

From Figure 8 the necessary furnace temperature can be found (for $X = 8.4$ and $m = 2.32$) to be $t_F = 1655$ F. The weight per unit hearth area, w_s, is:

$$w_s = 480 \text{ lb per cu ft} \times 5/12 \text{ ft} = 200 \text{ lb per sq ft}$$

If the length of the slabs is put on the width of the furnace, then $D_f = 3$ ft, and:

$$v = \frac{7200}{200 \times 3} = 12 \text{ ft per hr}$$

The length of the furnace (Eq. 20) is:

$$L_f = 12 \times 1.24 = 14.9 \text{ ft}$$

In Figure 114 the surface temperature is plotted *vs.* time and furnace position, the latter two to be measured on two scales of the abscissa axis.

Assume that the entire length of the furnace is divided into five sections, each of 3 ft length. The mean surface temperatures for the five sections are: 620, 1130, 1380, 1510, and 1580 F. The useful heat for each section is the product:

(furnace temperature − average surface temperature) × area
                                   × boundary conductance × 1/3413

The heated surface area of the charge in each section is $2 \times 3 \times 3 = 18$ sq ft. (Bottom and top receive heat.) The third zone, for instance, requires a useful heat of:

$$(1655 - 1380) \times 18 \times 37.5 \times 1/3413 = 54.4 \text{ kw}$$

For the five zones the useful heat values are: 204.6, 104, 54.4, 28.6, 14.8, the sum being 406.4 kw. The necessary input to raise the 7200 lb per hr to a mean temperature of 1590 F is:

$$\frac{7200 \times 0.128 \times (1590 - 70)}{3413} = 410 \text{ kw}$$

If in the first zone the average surface temperature is 620 F, then (from Fig. 9, Vol. I) the Ξ value is only 185 and, accordingly, $h = 25.2$. The useful heat thus transmitted in the first zone is only 137.6 kw instead of the 204.6 kw (calculated for $h = 37.5$). Making similar corrections in the second section and increasing the useful heat in the third through fifth sections results in a lower amount of useful heat transferred (approximately 337.4 kw instead of 406.4 kw). One of two measures can now be taken: either the furnace tem-
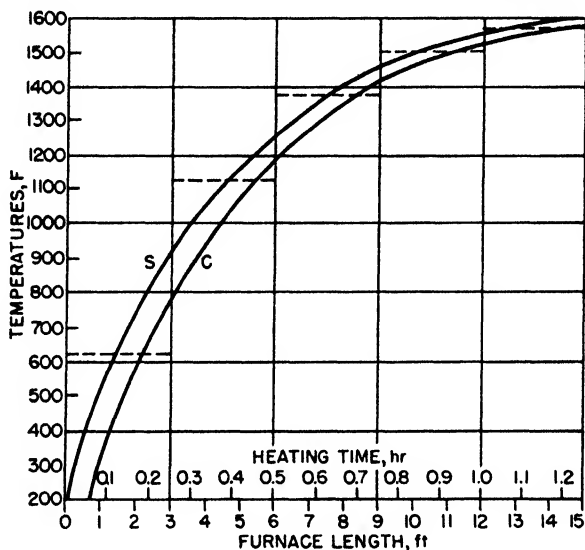
Fig. 114. Surface temperature (S) and center temperature (C) *vs.* time and furnace position.

perature in the first and second zone can be increased, which will result in a greater amount of heat transferred there; or the length of the furnace can be increased. The first measure will usually be taken, frequently supported by an increase of furnace length. If the furnace temperature is no longer constant, determination of the temperature increase from the available charts is no longer possible.

In counterflow furnaces the heat exchange between outgoing and ingoing charge must be estimated. Since this heat exchange is much more uniform under the influence of convection, this type of furnace will be discussed on pages 159–161.

4. High-Temperature Furnaces (Furnaces with Nonmetallic Resistors)

Furnaces beyond the range of metallic resistors can be classified as high-temperature furnaces. The division is not accurate because with progressing development of new alloys the temperature range for metallic resistors increases and because in certain cases nonmetallic resistors are used at relatively low temperatures, below 1800 F.

(a) Applications

The field of application of nonmetallic resistors is quite large because of the great number of industrial processes carried out at high temperatures which cannot be obtained with metallic resistors. Their use is narrowed by the use of direct heat furnaces and appliances, by conduction type furnaces, and in part by arc furnaces. As long as there are no metallic resistors for high temperatures available, furnaces with nonmetallic resistors have a definite field of usefulness. The following may give some information concerning more common uses of furnaces with nonmetallic resistors.

Furnaces of this type are being used for hardening high speed steels, occasionally for preheating for forging, for melting small batches of iron, steel, nonferrous metals, and glass, as well as for firing ceramic materials. The latter application, quite widespread in Europe, has not yet been introduced to American industry.

(b) Globar Furnaces

BOX TYPE FURNACE

The three general classifications are the horizontal side-fired furnace, the horizontal over- and under-fired, and the vertical side-fired having a row of elements mounted vertically on either side of the hearth plate. Each has advantages and disadvantages. In ceramic kilns, vertical side heaters are ordinarily used (see page 149).
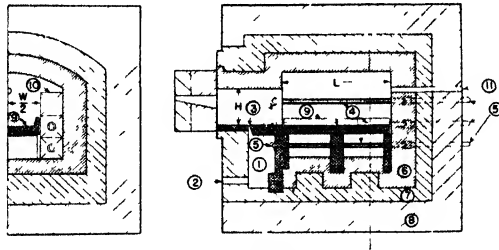
Fig. 115. High-temperature box type furnace. 1, atmosphere combustion chamber; 2, inlet; 3, slot emitting curtain of combusted gases; 4, heating elements; 5, terminals; 6, refractory lining; 7, semi-refractory insulation; 8, heat insulation; 9, hearth plate; 10, terminal bricks; 11, thermocouple opening. (Courtesy *C. I. Hayes, Inc.*)

Except for the heavier walls, used because of the high temperature, and for the difference in resistors, the high-temperature furnaces are built similarly to medium-temperature furnaces.

Figure 115 illustrates a box type furnace with horizontal resistors on the sidewall. The furnace provides for heating in protective atmosphere.

Globar resistors are used on both sidewalls and extend through the rear wall. The front ends of the resistors are pressed against terminals which extend through the sidewalls, perpendicular to the resistors. The charge is placed on a silicon-carbide hearth which is elevated above the furnace bottom, and receives heat by radiation from the lowest side heater on either side wall, the lowest heaters being located below the hearth level. Omission of resistors under the hearth simplifies the design, but, for reasons of uniformity of heating of the charge, limits the maximum width for which the furnace can be built.

On the front wall at the sill, a burner is placed which can be used for burning city gas, natural gas, or bottled gas. The pressure of the gas and air may be read on a manometer. By analyzing the gas, one can assign to each gas-air ratio, as established by the manometer, a given composition of the combusted product. Maintenance of uniform atmosphere composition is possible only as long as air and gas pressure do not change. The gas enters through a slot next to the door and fills the chamber. Discharge of extra gas takes place through a vent in the rear wall and through an opening in the door. A special valve automatically increases the flow of gas as soon as the door is opened. A gas curtain spreads over the opening and prevents infiltration of air.

CONTINUOUS CERAMIC KILNS

These have not as yet been built in the United States, but a number have been used in Switzerland, Italy, Germany, and France. Furnaces with one, two, or three separate chambers have been built. In the case of several chambers, one or two are employed for bisque firing; between these is usually placed the third, for glost firing. It has been estimated that, in 1940, a total of 20 electrically heated chambers for high-temperature heating of ceramic material were in operation.[55] Such furnaces are mostly used for firing stoneware, vitreous china, and semi-vitreous china, for bisque and glost firing, and for wall and floor tiles. Each chamber consists of three zones, i. e., preheat, high heat, and cooling. Usually only the second zone is heated, with provision for preheating of the charge by utilizing the heat content of the charge passing through the cooling zone. Frequently in two- or three-chamber furnaces an interchange provides that the preheating in the high temperature chamber is effected by utilizing the heat content of the charge cooling in the low-temperature chamber and vice versa. In some instances, small additional amounts of energy are necessary for the preheating zone of the high-temperature chamber. Generally only the high-heat zone of the high-temperature chamber is heated by silicon carbide resistors (Globar or Silit), with all other heated sections being equipped with metallic resistors.

[55] H. Masukowitz, Elektrowärme, 10, 1 (1940).

The heat exchange from the charge in the cooling zone to that in the preheating zone is generally done by circulating air. Thus the uneven cooling and preheating which would result, if the exchange took place merely by having two rows of charge parallel each other and heat exchanged by radiation only (see also page 302), is avoided. The charge is pushed through the furnaces on insulated cars. The car train is moved by hydraulic or pneumatic pushers at predetermined intervals. The chambers are kept closed, and the opening of doors and movement of cars are interlocked and timed automatically.

The economic success of these furnaces is based on the possibility of eliminating or greatly reducing saggers and firing furniture necessary in direct-fired furnaces. Hence, not only better utilization of furnace space results, but also considerable reduction of labor (80% of the labor used in continuous fuel-fired kilns, operating with saggers, is reported to be saved in electric kilns which do not require saggers), much faster heating, and a reduction in dead weight in a ratio of 1:3 or more; such reduction of course entails a considerable reduction of gross weight. The following heating times (in hr) have been maintained on the average in continuous electric kilns:

Vitreous china	35 hr
Fireclay	44 hr
Semivitreous china (bisque fire)	
Sanitary ware	35 hr
Chinaware	25 hr
Semivitreous china (glost fire)	
Sanitary ware	28 hr
Chinaware	22 hr

Savings by use of electric kilns are much smaller when the nature of the charge is such that contact with products of combustion is not objectionable and for which, therefore, the fuel-fired kilns do not operate with saggers. Power consumption is reported as follows:

Fireclay, vitreous china	0.6–0.7 kwhr/lb
Semivitreous china (bisque- and glost-fired combined)	0.6–0.9 kwhr/lb

Figure 116 is an inside view of such a furnace. Despite the fact that the furnaces have repeatedly been briefly described,[56] information about them appears to be incomplete.

[56] H. E. Meuche, *Elektrotech. Z.*, **59**, 1317 (1938). A. Rittgen, *Keram. Rundschau*, **47**, 275 (1939). A. Rittgen, *Elektrizitätswirtschaft*, **34**, 675 (1935); abstracted in *Ceram. Ind.*, **29**, 126, 198 (1937). A. Rittgen, *Ber. deut. keram. Ges.*, **19**, 113 (1938); translated in *Ceram. Ind.*, **32**, 43 (June, 1939) and **33**, 47 (July, 1939). P. Gatzke, *Ber. deut. keram. Ges.*, **17**, 297 (1936); translated in *Ceram. Ind.*, **27**, 267 (Oct., 1936). P. Gatzke, *Elektrowärme*, **8**, 196 (1938). H. Masukowitz, *ibid.*, **6**, 30, 123 (1936). Anon., *Bull. Schweiz. Elektrotech. Verein*, **28**, 455 (1937); translated in *Ceram. Ind.*, **31**, 29 (July, 1938).
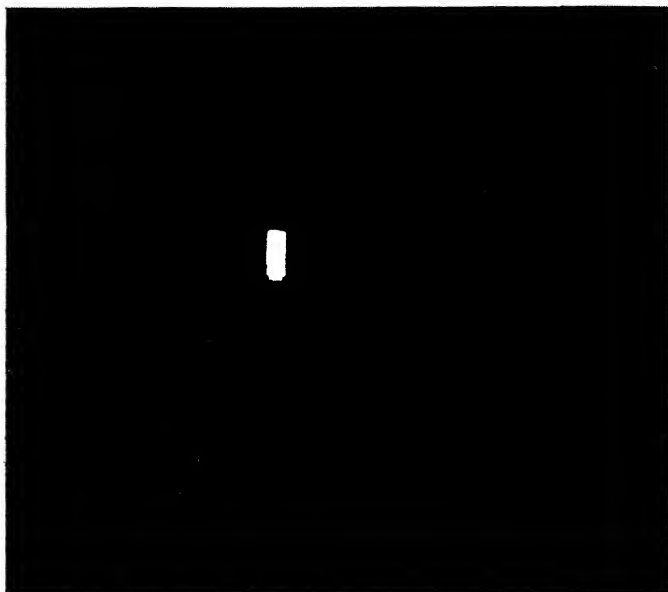
Fig. 116. Tunnel kiln for ceramic products.

DESIGN AND CALCULATION

With respect to necessary dimensions of the working space and to calculating the useful heat, the design of high-temperature furnaces does not differ from that of furnaces with metallic resistors. For the former, special questions arise however with respect to selection of number and size of resistor units and their spacing. The number of resistors depends, of course, on the connected load and the permissible energy density; an important difficulty is encountered in determining the connected load— the heat losses change with the number of units and their size. One should first estimate number and size of resistors, then determine the heat losses and, from these figures, the connected load; select the resistors, based on temperature and permissible energy density (see page 86); and if the estimate was too inaccurate, repeat the procedure.

In many high-temperature furnaces, particularly for tool-room hardening, the production to be obtained is not known accurately; then the connected load cannot be based on a definite amount of useful heat, and the contribution of heat losses caused by the resistor may be neglected in selecting the connected load.

The maximum permissible temperature for Globar resistors is 2950 F, which, generally speaking, permits the design of furnaces with operating (control) temperatures up to 2850 F or 2900 F maximum. At the ex-

treme temperature of 2950 F the permissible energy density is extremely small (*e. g.*, 5 w per sq in. at 2950 F; see page 86) and therefore the connected load is limited for a given size of the working chamber. Moreover, heat losses are high at the high temperatures and therefore the useful heat is still more limited. In general, commercial furnaces with this type of resistors can therefore not be used beyond approximately 2600 F.

The designing of highly insulated furnaces for materially lower temperatures raises the problem of providing sufficient elements without uneven heating of the charge.

From the formula (page 86) for energy density, one might easily arrive at very few resistors, which, from the viewpoint of resistor life, are not excessively hot, but which on the other hand do not cover the available area sufficiently and result in spotty heating of the charge. No definite rules can be given, because the desired spacing depends on the control temperature as well as on shape, size, and uniformity requirements of the charge. Spacing the resistors too closely results in mutual overheating. They cannot give off their energy except by increasing their respective temperatures locally in sections where radiation is limited.

The manufacturer's recommendation is that the center distance be between 2 or 3 d as minimum and 1.4 Y as maximum; d is the diameter of the Globar and Y the distance from the center line of the resistor to the surface of the load.

A purely empirical figure is sometimes recommended as a check: the ratio of the chamber volume (in cu in.) to the combined surface of all heating elements (in sq in.) should not exceed 4 in.

Selection of the distance between resistors and wall is governed by several factors. Too close a spacing results in uneven heating of the surface of the resistors next to the wall, subsequent failure, and also uneven heating of the charge. Too great a distance from the wall increases the heat losses unduly. The manufacturer recommends that the distance between resistor and wall should be at least one element diameter.

It should be understood that these rules are indicative only, and may be subject to change in special cases.

The number and spacing of resistors having been decided, the proper subdivision between top and bottom load is chosen. In view of convective heat flow in the furnace chamber, somewhat more energy should be provided in the resistors under the hearth than in those at the roof. However, the elements under the hearth are shielded and for this reason apt to overheat. Therefore the energy density of the bottom resistors under the hearth should be somewhat lower than that of the top heaters. This question is rather controversial and is an important field for investigation.

When size, rating, and energy density for the resistors have been chosen, the voltage is selected. Since a transformer is necessary to adjust for change of resistance with life, the ratio of the voltage of the individual rod to the supply voltage need not be unity or a round fraction ($\frac{1}{2}$, $\frac{1}{3}$, etc.).

It might appear desirable to connect the resistors initially in series; when their resistance increases, connections could be changed to "parallel." Thus, for a given desired voltage range, the control transformer could be smaller. This method would work well if all resistors in any one group in series connection had initially, as well as at any later time, the same resistance. However, they do not always have the same resistance, and parallel connection is then preferable for the following reason.

For series connection the resistor within the highest resistance carries the heaviest load and tends therefore to become hotter and increase its resistance further. In parallel connection, the resistor with the highest resistance carries the smallest load and thus allows the other resistors to "catch up."

Most Globar elements operate in air, but there are also a number of furnaces operating with reducing atmospheres. Mixtures of carbon monoxide and carbon dioxide apparently do not affect the life of Globar materially whereas an excess of hydrogen proves detrimental, particularly at temperatures above 2550 F. Salt vapors and splashes of molten metal in melting furnaces (*e. g.*, aluminum) on the Globar shorten the life of the latter appreciably.

(c) George Furnace (Furnace with Graphite Rod Resistors)

H. George designed a furnace with one or more graphite rods in the center of a chamber into which material to be melted is placed.[57] In order to prevent too high a graphite consumption the furnace is made gas-tight. The air present at the start of a heating cycle burns the surface of the electrode and yields a carbon monoxide atmosphere in the furnace chamber.

The electrodes are placed entirely within the furnace; carbon pieces press against the electrode and carry a water-cooled current connector. In the original French design the electrode was kept rather short, holding the contact area in the furnace chamber proper. Each contact consisted of several pieces, some graphite, some carbon, thus increasing the number of contact points which the current must pass. The idea was that, because of the location of the contact, the unavoidable heat generated by it would be utilized in the furnace. A later German modification[58] is similar to the previously described water-cooled Globar contacts, in which

[57] H. George, *Trans. Electrochem. Soc.*, **68**, 53 (1935).
[58] O. Gengenbach, *Elektrowärme*, **8**, 172 (1938).

the contacts are placed flush with the inner furnace wall, and only. one solid piece is used for each contact.   The contacts are so arranged that they can easily be removed, by hand from small furnaces, or on special carriages from large furnaces.   Changing resistors is quite easy, and, moreover, the resistors can be withdrawn from the furnace during charging.

Because of the high currents used in the graphite resistor, special attention should be paid to the return leads of the resistors.   Together with the latter, the leads to the transformer form a loop and there is danger of an undesirably low power factor.   This difficulty is overcome by using the furnace shell as return lead, and for larger furnaces with single-phase currents of 10,000 amp or more, a copper cylinder is placed immediately inside the outside steel shell, thus preventing the steel shell from acting as a transformer core.   The power factor even of large furnaces ranges from 0.9 to 1.0.   The high power factor is in part a result
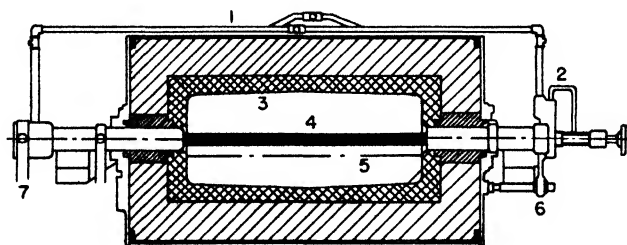
Fig. 117.   Melting furnace with graphite rod resistor: (1) tubing for water cooling; (2) handle for extraction of graphite rod; (3) refractory lining; (4) graphite rod; (5) molten bath; (6) current connection; (7) bus connections.

of the design providing for the transformer to be very close to the furnace, forming an integral unit with it.

Figure 117 [58] shows a cross section through a single-phase furnace of this type.   For large connected loads, three-phase furnaces are used, with three graphite resistors arranged either at 120 degree angles in the center of a round furnace, or in one plane above the bath of a fairly low rectangular furnace which might be called an electric reverbatory furnace.

The diameter of the resistors is selected within a range of $1\frac{1}{2}$ to $2\frac{1}{2}$ in., depending upon the connected load.   As the graphite burns off, the voltage must be increased, but for reasons of mechanical strength rods of $\frac{3}{4}$-in. diameter or less must be discarded.   The graphite consumption is approximately 1.6 to 2.0 lb per 1000 lb of steel produced (at 3000 F); this figure compares with a consumption of 7.5 lb per 1000 lb as average for arc furnaces (see Vol. I, page 134).

Some time is required for a furnace, started cold in the morning, to become saturated with heat. Consequently, the first charges take longer and consume more energy than charges poured later in the day. The melting time depends, of course, largely on the connected load. Data published so far indicate melting times and power consumption in the same order of magnitude as in arc furnaces. This furnace type, then, promises to be useful, mainly in small production jobs, foundries with frequently changing composition, etc.

The design of this furnace resembles somewhat that of the indirect arc furnace (Vol. I, page 103). The heat source in the George furnaces is longer (extending over the entire length of the furnace) than that in an indirect-arc furnace (in which the arc extends, of course, only part of the length of the furnace). The radiating area of the resistor is larger than that of the arc, and the resistor temperatures are lower than arc temperatures. The voltage applied to the resistor in the George furnace is lower than that in the indirect-arc furnace.

B. Convection Type Furnaces

1. Applications and Types

The field of application for convection type furnaces is constantly growing. These furnaces are used in drawing and hardening steel, age hardening and other heat-treating operations for aluminum and light metals, annealing of brass and copper, heating of zinc for rolling, cooling zones of annealing furnaces for steel, periodic glass lehrs, the low-temperature zones of ceramic kilns, and in almost any operation in which furnace temperatures are below approximately 1200 or 1300 F. The above examples do not include cases in which moving air is necessary for the process, as in drying. Moreover, convection type furnaces find an increasing field of legitimate application for higher temperatures if the charge consists of a number of small individual pieces and the air can be forced between the pieces, thus decreasing the "critical" dimension or thickness for heating (see page 27).

To some extent the advantages of convection heating are exaggerated resulting in the danger of application where its use is really not warranted.

True convection type furnaces have a heat source outside the furnace chamber and insulated from it. Air or gases are heated by this source and then passed over or through the charge, thus releasing part of their heat content to the charge. Convection type furnaces can be grouped into stationary and continuous types. In the latter the flow of air may be in the same direction, or opposite to the direction of the flow of material, or even at right angles to it. The "basic considerations" in the section on calculation hold for all these types.

In heating some types of charges, the air may be forced through the charge; in other cases it flows around the charge. In the first case the length of the air path in the furnace must not be too long in order to avoid excessive pressure drop. Generally speaking, output and uniformity of convection type furnaces are improved if the amount of circulating air is increased; but a limit to the amount of air may be reached because of blower size, which also increases with amount and velocity of circulating air.

Since in radiation furnaces blowers or fans are frequently used for circulating the furnace atmosphere, such furnaces may be classified as "combined convection and radiation furnaces." Although, undoubtedly, the rate of heating of the charge is improved, the flow of air is so indefinite in these furnaces that the calculation of the heat transfer is still not possible.

2. Furnace Design

(a) *Pure Convection Types*

BATCH TYPE FURNACES AND OVENS

Of the many different designs developed, only a few can be reviewed here. To avoid radiation from the resistors to the charge, it is necessary to place them either behind a shield or in a separate heater chamber.
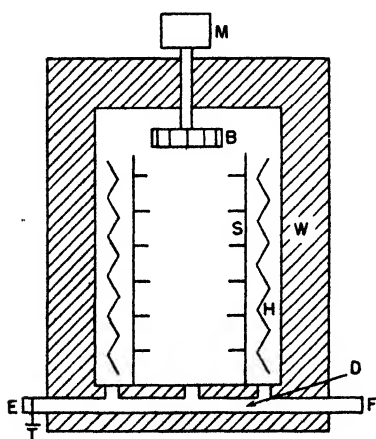
FIG. 118. Convection furnace with shielded resistors in working chamber.

Figure 118 shows an oven with shielded resistors. Air is forced through the charge by means of a fan or blower, *B*, driven by motor *M*. The air then is drawn from the intake *F* through ducts *D*, and part is ejected through an outlet, *E*, and part recirculated along the resistors, *H*, which are located between wall *W* and shield *S*. By means of a damper, *T*, the ratio of recirculated air to fresh air can be adjusted. Fresh air is admitted through intake *F*. The wall consists of two steel shells between which insulation is placed. Special designs (Fig. 119) are used to minimize thermal short circuits between the two walls.

A box type furnace with a separate heating chamber is shown in Figure 120. The entire resistor set, together with a cover, can be withdrawn from the chamber for inspection, repair, and replacement. Guides are arranged near the top to distribute the air stream as evenly as possible.
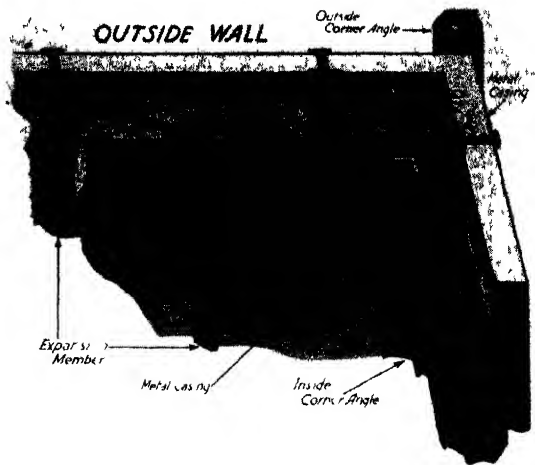
FIG. 119 Wall design for low-temperature work. (Courtesy *Gehnrich Oven Div. W. S. Rockwell Co.*)
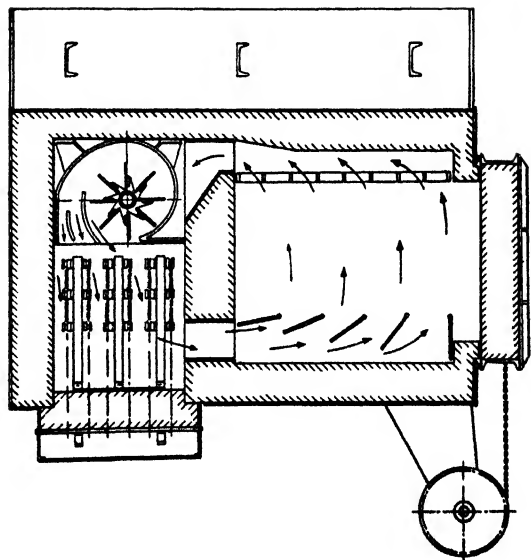
FIG. 120. Box type convection furnace with separate heater chamber. (Courtesy *Lindberg Engineering Company.*)

Convection furnaces with horizontal working opening (Fig. 121) are useful in the field of light metals. They permit quick and efficient quenching. The charge rests on a car bottom. When it is heated through, it is raised slightly, the door opened, and the car which stood over a quench tank is withdrawn. As soon as the quench tank is accessible, the charge is quickly lowered to a dolly at the bottom of the tank. In the meantime the car bottom of the furnace has been reloaded and the next charge is placed into the furnace. The dolly at the bottom of the quench tank is pushed to the left and then raised out of the tank.
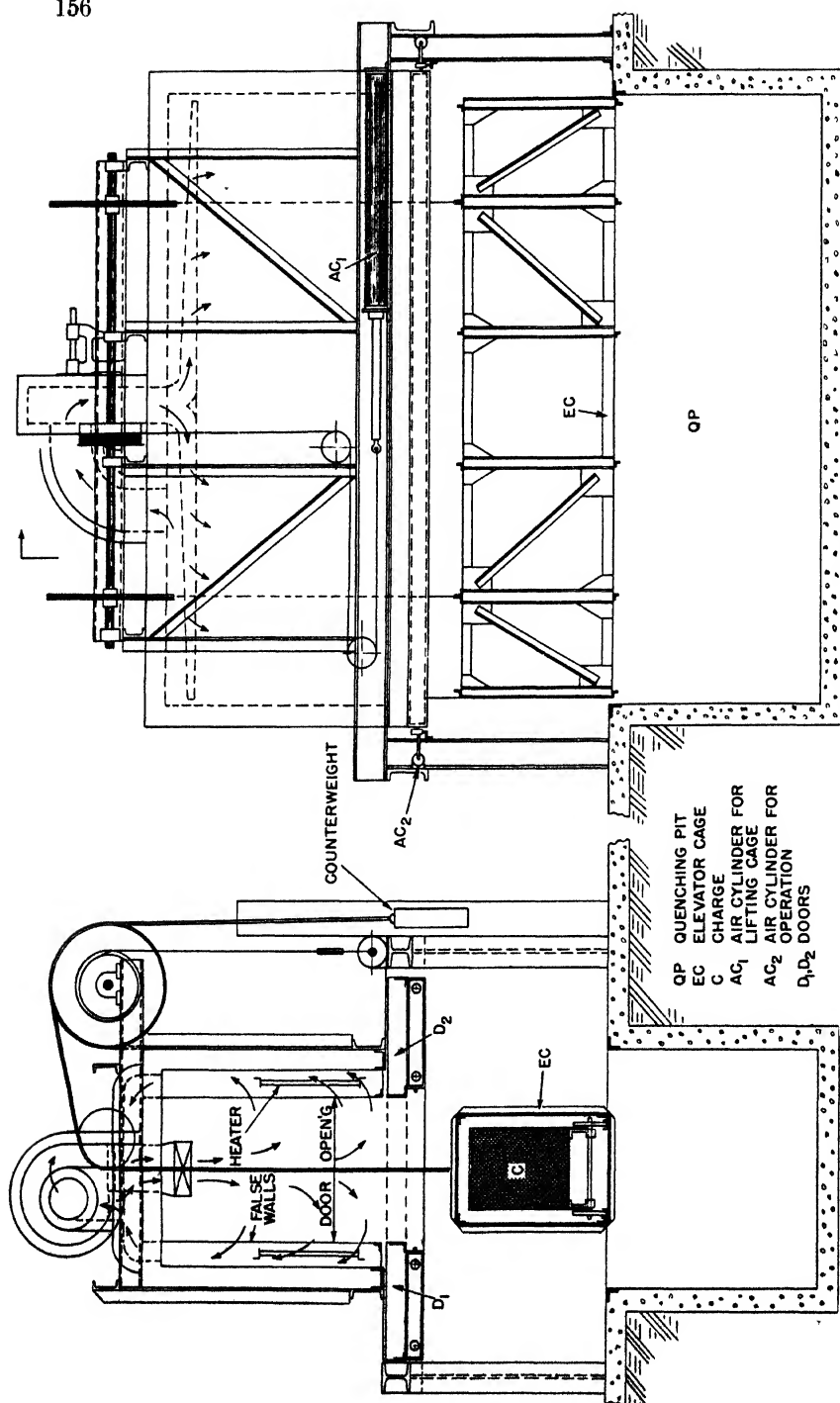
Fɪɢ. 121. Convection furnace with horizontal working opening—bottom quench. (Courtesy *Young Brothers Company*.)
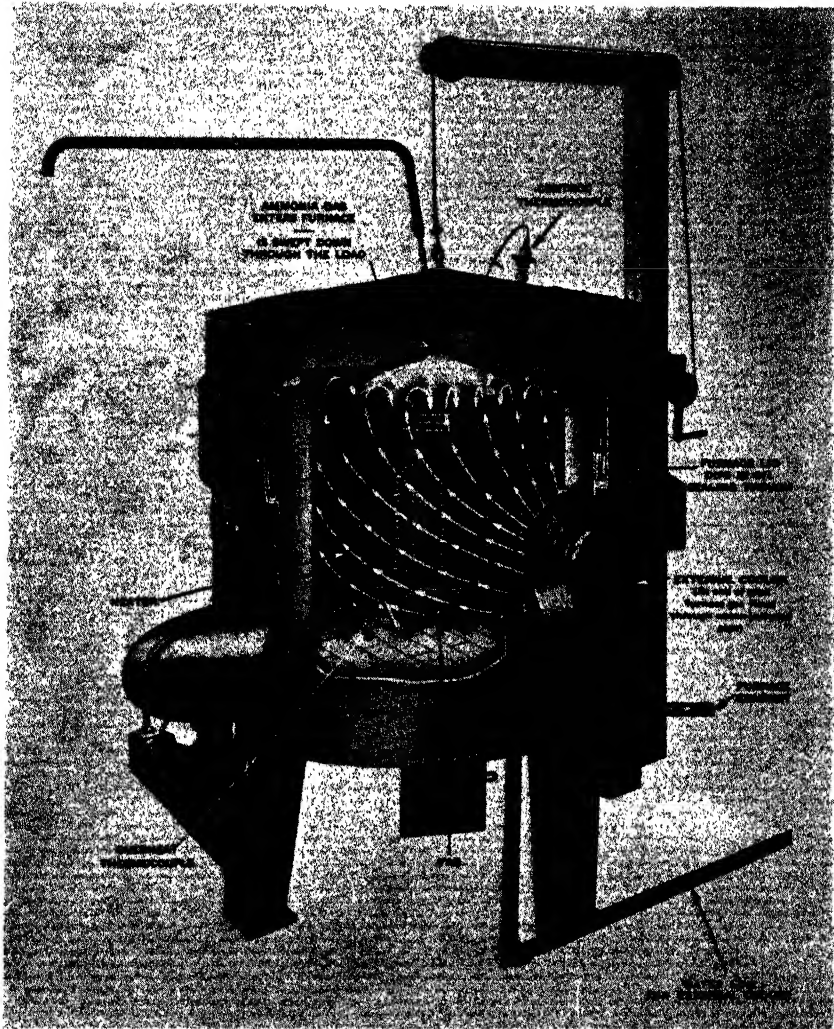
FIG. 122. Convection furnace with prepared atmosphere—nitriding furnace. (Courtesy *Leeds & Northrup Company*.)

The application of convection type furnaces to heating processes using artificial atmospheres offers the advantage of not only heating more rapidly and uniformly as in convection furnaces with circulating air, but of giving also all parts of the surface a more uniform application of the atmosphere. An example of a convection furnace with prepared atmosphere is the nitriding furnace shown in Figure 122. Nitriding consists of exposing certain types of steel to an ammonia atmosphere at temperatures

FIG 123.   Resistors for furnace (Fig 122)   (Courtesy *Leeds & Northrup Company.*)

between 900 and 1000 F   The surface picks up nitrogen and thus builds up hardness.   The charge must cool in the furnace.   To accelerate cooling of the furnace, gases are passed through a cooling pipe during the cooling period.   Figure 123 shows a cutaway picture of the furnace.   The charge is placed in a container, which in turn is placed in the furnace chamber.   The wall of the container acts as a radiation shield.   The gas entering through the cover is drawn through the charge by means of the fan and recirculates over the heaters.   The latter are mounted on a metal frame by means of insulators, separating the resistors from the lining. The fan, placed at the bottom of the pot, may be seen.   At the end
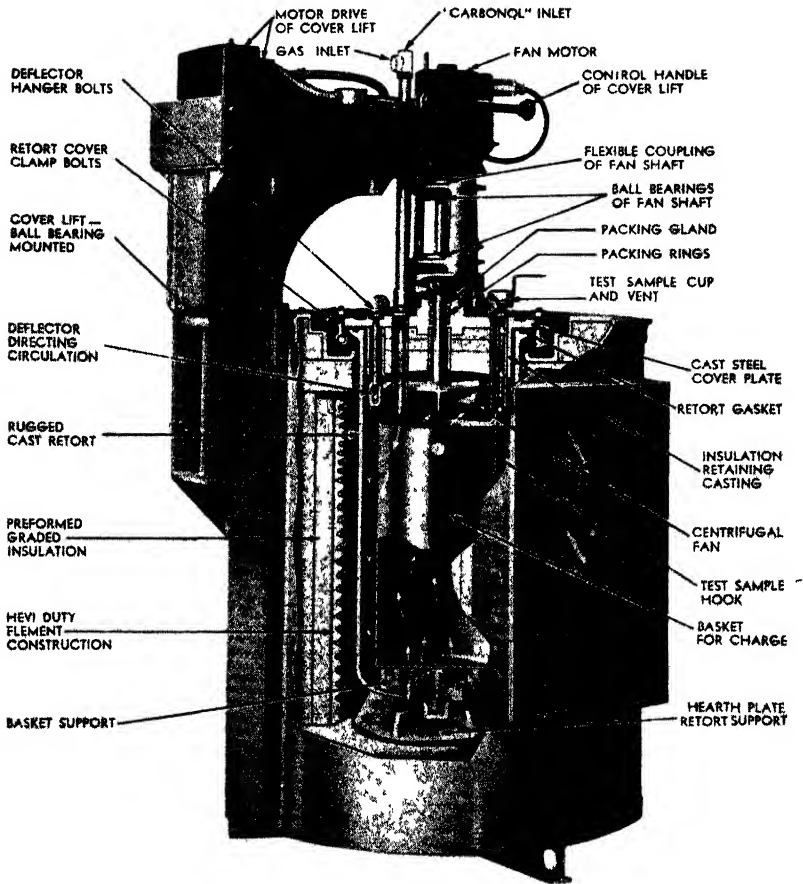
FIG. 124. Gas carburizing furnace. (Courtesy *Hevi Duty Electric Company.*)

of the heating period, the inlets to an external cooler, which consists of a water-jacketed pipe, are opened. The gas circulates through the pipe and the furnace and thus cools the charge.

Gas carburizing is another application of convection type furnaces (Fig. 124).

CONTINUOUS FURNACES AND OVENS

In continuous furnaces the air (or gas) stream can be either parallel or perpendicular to the flow of the charge. If the charge and air flow in parallel lines, they can go either in the same direction (parallel flow) or in opposite directions (counterflow). Figure 125 shows diagrammatically

a parallel flow furnace and the nature of temperature-space curves (air temperature and charge surface temperature plotted *vs.* distance from the entrance). In counterflow furnaces (Fig. 126), the charge is heated with less thermal shock and at a more uniform rate. Counterflow fur-
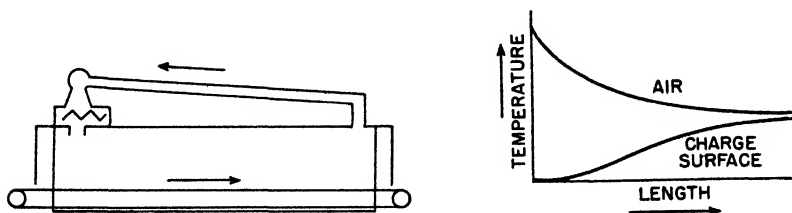
Fig. 125. Principle of parallel flow furnace.
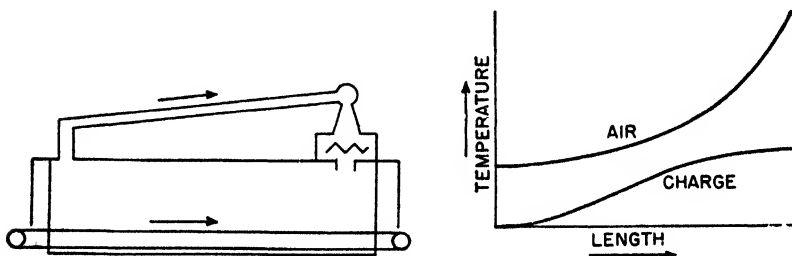
Fig. 126. Principle of counterflow furnace.

naces are particularly advantageous where the charge may cool in the furnace or oven. A typical example would be ovens for drying varnish or lacquer on steel or castings. For such recuperative ovens the heaters are placed in the center of the furnace. This type of oven is more easily built for mixed radiation and convection heating (Fig. 132).

In continuous furnaces with longitudinal flow, air infiltration through leakage from the door openings must be prevented. If the continuous movement of the charge is replaced by regularly intermittent steps (*e. g.*, walking beam furnaces, trains of cars), doors can be kept closed except during the short moments of actual movement. If continuous movement is necessary, chain screens through which the charge can pass unhindered offer quite effective resistance to undesired air flow through the openings. Such chain screens can be applied only if the individual pieces of the charge are heavy enough to avoid being tipped over by the chains of the curtain, and if the chain will not damage the surface. Curtains of asbestos strips have been applied successfully for lighter material with sensitive surface.

Optionally, or in addition to screens, the opening should be reduced to fit as nearly as possible the cross section of the charge. Finally, guides (Fig. 127) next to air inlets and outlets can be used to increase the resistance of the air in undesired directions.

Cross flow, perpendicular to the direction of motion, can be either in vertical direction or horizontally over the charge (Fig. 128). The choice depends on the nature of the charge. If the latter consists of
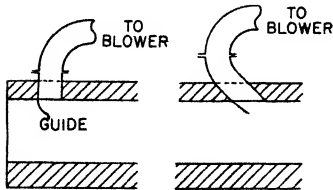
FIG. 127. Guides for air inlet and outlet.
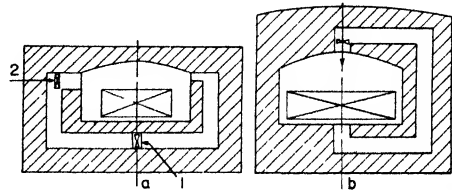
FIG. 128. Arrangement for cross flow of air: a, horizontal; b, vertical.

several pieces and if spaces between the individual pieces are sufficiently large to permit passage of air, the air flow should be so directed that air is forced through these openings. If the charge consists of individual pieces, several piled upon each other, or of coils where the spaces between the individual layers are not large enough to permit penetration of air, the air should be so directed that a uniform flow of heat results (pages 29 and 165).

The horizontal flow of air as shown in Figure 128 sometimes offers design difficulties in placing the blower. In position 1, the shaft of the blower must be long. If position 2 is selected with an axial flow blower, the discharge opening must be high enough that the air stream flows over the charge and does not strike the side. Uniform distribution of the air above and below the surface is difficult to achieve. It is possible to place the blower entirely outside the furnace, closing the air circuit through outside pipes (Fig. 129), a design which can be applied to vertical and horizontal air flow. Also, combinations of the types shown in Figure 128 and 129 can be used, with some of the pipes inside the insulation and some, including a blower chamber, outside. Any pipes or ducts out-

FIG. 129. Blower outside the furnace.

side the furnace should be insulated. Since high velocities are desirable, it is well to minimize the furnace cross section available to air flow. Large furnace spaces, filled only partly by the charge, are wasteful not only because of high heat losses, but also because of resulting low air velocities and poor heat transfer rates.

(b) Combined Heating

Combined heating furnaces have resistors radiating directly to the charge and in addition blowers or fans to circulate air. Generally there are no separate resistors to heat the air; rather, the air transfers by convection part of the heat that the same resistors would otherwise radiate to the charge. In simple designs the air is merely swirled around in the furnace (Fig. 130); in more complex designs the air is forced over the

Fig. 130. Combined radiation convection furnace.
(Courtesy *Hevi Duty Electric Company*.)

resistors (Fig. 131). The effect of air circulation in such instances is mainly to avoid cold spots in those parts of the charge difficult to heat by radiation. However, the degree of uniformity which can thus be obtained is hard to predict. The air flow pattern depends on the arrangement of the charge in the furnace, and in many instances the air will be in contact mainly with those parts of the charge which are exposed to radiant heat. Desired heating rates, difficult to maintain in straight convection furnaces, are still less controllable in combined furnaces, in which a change in input

influences radiation and convection to different degrees, and a change in air velocity influences the ratio of the heat transferred by radiation to that transferred by convection.

In low-temperature continuous ovens, such combined heating has a legitimate place, because the flow of air may serve for heat recuperation. Figure 132 illustrates such an oven in which heating elements are in the center, and charge and air move in opposite directions. The cold air strikes the outcoming charge, picks up some heat, and flows into the heated part of the oven where it is heated further by the resistors, thus reaching its maximum temperature. Thence the air flows into the preheat zone, where it delivers heat to the incoming charge and is thus cooled. The heaters do not supply the entire heat necessary to bring charge and air to the temperature in the high-heat zone, but rather only

FIG 131. Combined radiation convection furnace.

the heat losses from the walls, plus the heat content of the outgoing charge and air, which are both at lower temperature than in the high-heat zone. The balance of heat contained in air and charge at their respective exit from the high-heat zone is obtained by heat exchange in the outer zones.
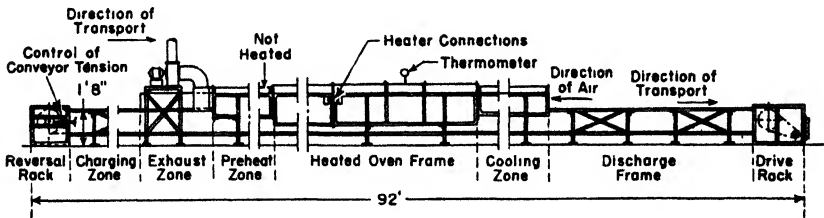
FIG. 132. Combined radiation convection furnace (counterflow of air and charge).

Figures 133 and 134 demonstrate this principle as applied to space-saving designs. Figure 133 is a two-story oven, with the return conveyor above the ingoing conveyor, and resistors on one end of the oven chamber. Figure 134 is a vertical core-baking oven, with resistors concentrated in the top section of the oven.

(c) Summary

For some of the more common types of charges the proper method of convection heating may be summarized.

Tubes and Rods. Short lengths, up to perhaps 2 to 3 ft: longitudinal air flow. Rods should be separated into several layers (Fig. 135a); for
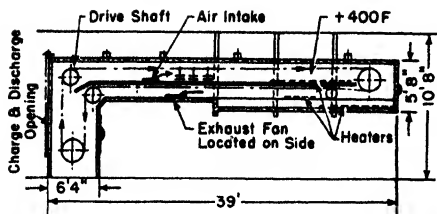
FIG. 133. Two-story oven. Loading and unloading by one operator. The space under the horizontal branch of the oven can be utilized.
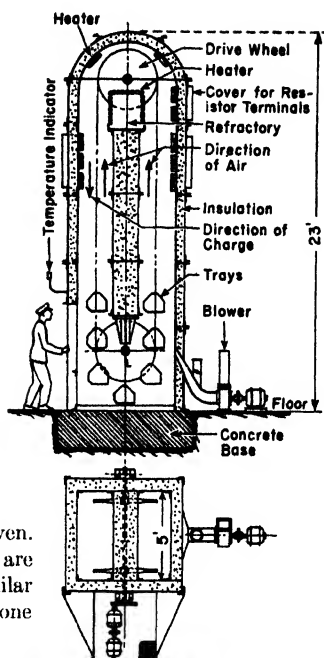
FIG. 134. Vertical core baking oven. Cores on perforated metal sheets are placed on trays. Only cores of similar drying time can be handled at any one time.

tubes and pipes such separation is desirable but piling tubes on top of each other is permissible (Fig. 135b) because a great part of the air will flow through the tubes or pipes.   Pipes and rods of great length: longi-
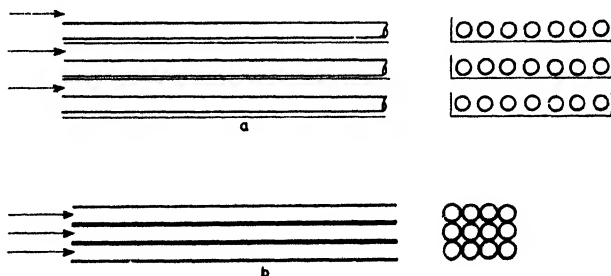
FIG. 135.   Longitudinal air flow for heating rods (a) and tubes (b).

tudinal flow would result in too great a temperature difference between front and rear of the furnace.   Reversing the direction of the air flow helps some for rods and tubes of medium length.   However, transverse flow as shown in Figure 136 is better.

Coils of Strip Metal.   Air should flow perpendicularly to laminations [59] (Fig. 137) either lengthwise (left side of illustration, arrows a) or

[59] V. Paschkis and J. A. Doyle, *Wire and Wire Products*, 21, 369 (1946).

transversely (by outlets *b* shown at the right side of the illustration) but never parallel to the laminations (arrows *c*).

Piles of Sheets. Air should flow perpendicularly to laminations, entering the furnace at *a* and leaving it at *b* (Fig. 138). The pile of sheets, *c*,

FIG. 136. Transverse air flow for heating tubes and rods: *A*, rack with load; *B*, perforated distribution shield to make air flow uniform across *A*; *C*, return pipe for air (may be placed in furnace wall); return pipe contains (not shown in figure) blower and heater.
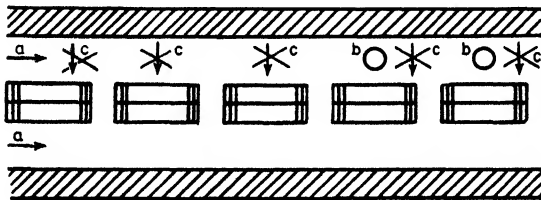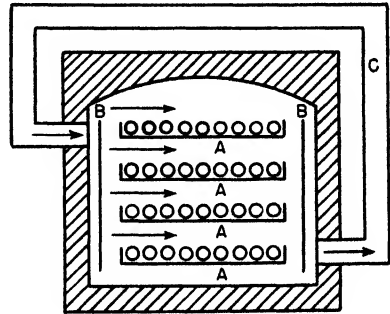
FIG. 137. Air flow for heating coils of strip.
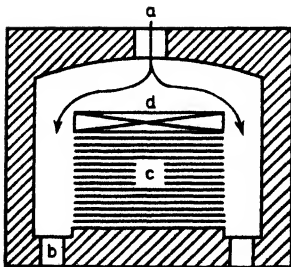
FIG. 138. Air flow for heating piles of sheets.

should be protected by some means (indicated by *d*) from receiving heat by air impinging on the top sheet. Either a heavy steel plate or, preferably, light-weight insulation would serve this purpose.

Wire Coils. If uniform heating is to be achieved (Fig. 139) the air should be forced between the individual strands of wire or rod, which is possible only in loosely wound coils. To avoid the air by-passing the coils and contacting only the outside strands, the space between the furnace body, *g*, and the coils, *c*, as well as the center of the coils should be filled with inserts (*d* and *e*) which fit the coil as tightly as practically possible, thus forcing the air to flow through the coil. The coils are supported in such a manner that the air can escape from the bottom of the furnace (supports shown schematically as points). In tightly wound coils, and when wire is wound on spools, complete uniformity of tem-

perature between inside and outside layers of wire cannot be obtained. Air flow should be so directed that all coils or spools are exposed to as nearly equal air flow and temperature patterns as possible.
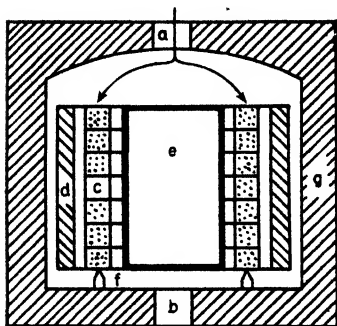
FIG. 139.   Heating of wire coils

Piles of Bolts, Nuts, Rivets, Small Castings, etc. Miscellaneous small parts, if heated in convection furnaces, are best placed in baskets, and the air forced through in either direction. The basket should fit as tightly as possible in the furnace to force the air through the charge and reduce by-passing to a safe degree. If the basket is much smaller than the furnace, fillers similar to part *d* (Fig. 139) can be used. Any method of heating in piles is less uniform than heating of individual pieces as on a conveyor covered by the material of only one layer thickness or in properly designated rotary drum furnaces.

Individual Large Pieces. No general rules can be given concerning direction of flow. Geometry of the piece and method of supporting and direction of air flow should be coordinated to insure uniform impingement of air.

3. Calculations

(a) *Basic Considerations*

The operation of convection furnaces can be understood from Figure 140. The illustration on the left shows the circulation of air, picking up
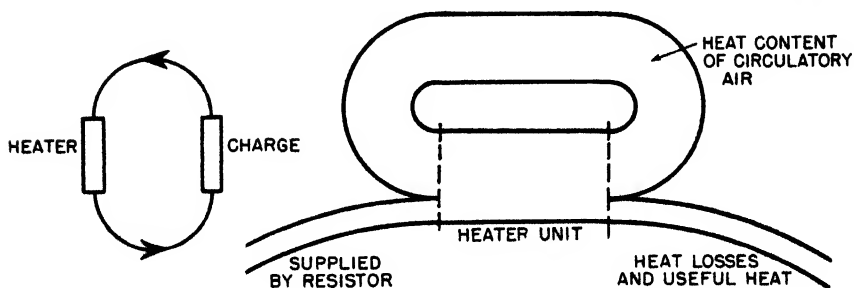
FIG. 140.   Convection furnaces as heat exchangers.

heat from the heater, and discharging heat into the charge. A diagram of heat flow is shown on the right. Of the total heat content of the air upon leaving the center, part goes into the charge and part returns to the

heater, where only the balance of the total heat contained in the air at the exit of the heater needs be added through the resistors. In batch type furnaces, the magnitude of each individual flow (width in the diagram) changes with time. The width and proportions of the various streams characterize the design of a furnace.

Figure 140 demonstrates that convection type furnaces are really heat exchangers. In the radiation type, heat is transferred once, namely from the heat source to the charge. In the conduction type, heat is transferred either once or twice; but if it is transferred twice, straight heat flow prevails (as in externally heated pot furnaces from the resistor to the pot, from the pot through salt, lead, or oil to the charge).
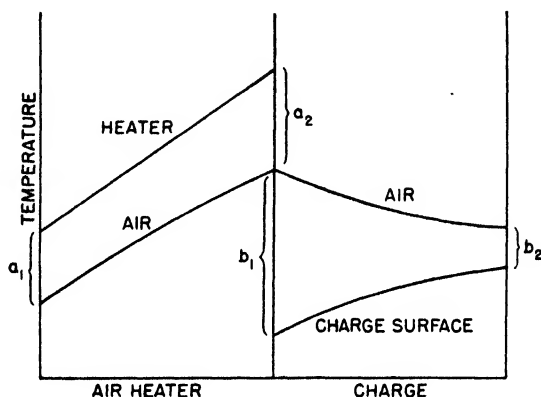
FIG. 141. Temperatures in air heater and charge chamber plotted against length of path in either chamber. Temperature differences increase in the air heater from a_1 to a_2 and decrease in the charge chamber from b_1 to b_2.

In convection type furnaces the air is actually circulating and the temperature of any one air particle changes periodically with time. In Figure 141, the length of the path of air along the resistors and along (or across) the charge are plotted as abscissas, and temperatures as ordinates. The heater increases its temperature from the air entrance to the air exit. (It is assumed that an equal amount of energy is liberated per unit resistor area.) The air entering the heater at a temperature slightly above that of the charge, picks up heat, and leaves the heater at an appreciably higher temperature. It strikes the other end of the charge which is substantially colder than the now heated air. During the contact of air and charge their respective temperatures approach each other, the air temperature dropping, the charge temperature increasing. At the air exit, the air temperature is only slightly higher than the charge temperature.

The schematic diagram (Fig. 141) can apply either to any one instance of heating in a batch type furnace, or to one section of a continuous furnace with several sections, or to a continuous furnace with one section.

So far only the problems of heat transfer in convection furnaces have been considered. There is, however, a second condition that must be met: over any given time period and for any one section of the furnace, or the entire furnace, the loss in heat content of the air equals the gain in heat content of the charge plus the heat loss through the walls. It is therefore evident that there are two laws to satisfy: the law of heat transfer and the law of heat contents. Although stated separately they are not independent.

In a batch type furnace, the temperature of the air entering the chamber is controlled automatically. By assuming a certain weight of air being circulated, the temperature of the air between entrance and exit will drop materially because the charge is cold. If the surface of the charge is great and the velocity of the air is high, so that there is good heat transfer, the air during its contact with the charge may cool so far that the connected load of the heater is not sufficient to raise the air temperature to the control point. Then the air temperature, even at the point of first contact with the charge (entrance) will be lower than the final temperature of the charge. Gradually, as the surface temperature of the charge builds up, less heat is being transferred from the air to the charge; the temperature of the air leaving the working chamber increases, as does that of the incoming air if too low. Finally, the charge will be almost at the desired temperature.

At this point the temperature drop of the air from entrance to exit will be determined by the heat losses. The rate of heat losses (Btu per hr) equals the temperature drop (F) of the air, times the hourly weight of the air (lb per hr), times the specific heat of the air at operating conditions (Btu per lb, F). This temperature drop is reproduced in the charge. Theoretically the temperature of the part of the charge near the air exit will continue to show an increase, which, however, is negligible.

What happens if the hourly weight of air is changed? The geometry of furnace and charge as well as the connected load are unchanged, and therefore the total amount of heat produced in the heater remains the same. If the quantity of air is very small, the air leaving the heater will always be heated to the control temperature. Due to its small heat-carrying capacity, the air will show a rapid drop in temperature, returning cold to the heater chamber. Only after a long period will the temperature of the charge begin to rise near the air exit, the air returning to the heater becoming warmer.

If the quantity of air becomes very large, the time for reaching the control point is hardly dependent on the hourly volume of air. Increase

in air delays only slightly the time for reaching the control point beyond a certain value. If the boundary conductance would not change with velocity, a definite upper limit would be reached, when the surface of the charge absorbs all the heat carried by the air.

The charge would then heat at constant rate of energy input. Conditions are schematically shown in Figure 142, where values of hourly volume are plotted as abscissas and times for reaching the control point (air temperature at entrance in furnace chamber = control temperature) as ordinates. Auxiliary diagrams show (Fig. 142, a and b) for two different values of hourly volume, air temperatures plotted vs. times. Increase of weight of charge would move the curve in direction of arrows 2, decrease of surface area in direction of arrows 1.

In continuous furnaces with several blowers moving air streams perpendicular to the direction of flow of material, each blower zone can be considered individually and can be thought of as a batch type furnace. The time required for a piece to travel through a zone corresponds to the time of a batch in the batch type furnace. The entrance as well as the exit temperatures of the charge differ for each zone, and, particularly in the initial zones, no attempt is made to attain complete uniformity of charge temperatures.

The above description of heating in batch type furnaces shows

FIG. 142. Heating time vs. circulating volume. At point A the product of volume per hour × temperature difference (control point — outside temperature) × specific heat of air equals the connected load. For volumes between O–A the connected load is sufficient to heat the circulating air immediately to the control temperature. Auxiliary diagrams a and b: Temperature of air entering and leaving the work chamber, plotted vs. time— (a) for times between O and A, and (b) for times later than B; from B on the time needed to influence the control point is governed by the charge alone.

that, mainly in the first stages of heating, the charge near the air entrance is materially hotter than the charge near the air exit. In continuous furnaces, alternating the position of blowers would be desirable (Fig. 143), but would entail mechanical design difficulties.

The several zones are not independent of each other. The temperature increase of the charge in each zone is determined by the two condi-

tions mentioned above: heat transfer and heat balance between air and charge—both influenced by the initial charge temperature, which in turn is determined by the preceding zones.
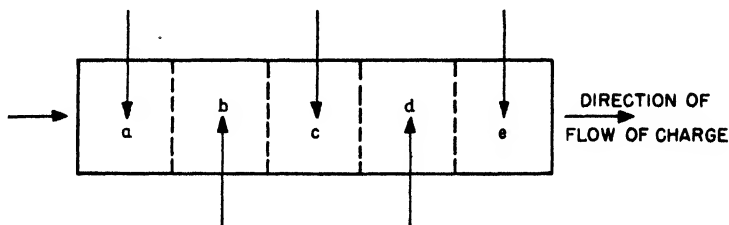
Fig. 143.   Furnace with alternating positions of blowers: *a–e*, blower zones.   Blowers in zones *a*, *c*, and *e* operate in a direction opposite to those in zones *b* and *d*.

For example, in a continuous furnace for which the total connected load is determined correctly, the subdivision of that load to the heaters for each blower is made without considering the interrelation of the zones.   The first zone may have too high a connected load, resulting in too low a load in one or more of the other zones.   Therefore, in the first zone the heat balance will be maintained without difficulty; the heat content of the air will be sufficient to heat the charge, but heat transfer to the desired extent will not be possible. The temperature control will cut in and out, because within the travel time of the charge in the zone the charge cannot absorb more than a certain amount of heat.   In the following zones the lack of sufficient connected load will result in a lower final temperature.   Similar conditions exist if the first zone has not enough connected load.

In counterflow furnaces, in which charge and air stream move in opposite directions, only one temperature control zone is possible.   The temperature of the incoming air, or the surface temperature of the outgoing charge, can form the basis of operation of the control equipment. The length of the furnace may be considered as being subdivided into a number of sections.   The air entrance temperature of each section equals the air exit temperature of the following section, and the charge-surface exit temperature in each section equals the charge-surface entrance temperature in the following section.   In each section the two laws are jointly active; again, if either air quantity or velocity is insufficient, the charge will not heat up completely.

(b) Calculation of Heat Content

Basically the law of heat content is very simple: *The heat absorbed by the charge equals the heat liberated by the air:*

$$V_c(t_{c_2} - t_{c_1})c_c\gamma_c = V_a(t_{a_1} - t_{a_2})c_a\gamma_a \qquad (21)$$

where t_{c_1}, and t_{c_2} are the mean temperatures of the charge at times 1 and 2,

$c_c\gamma_c$ is the volumetric specific heat of charge, $c_a\gamma_a$ is specific heat $\times$ density of air, V_c is the volume of charge (including fixtures), V_a is the volume of air, and t_{a_1} and t_{a_2} are air temperatures at times 1 and 2.

Difficulties arise from the fact that c and γ for air and the charge are in themselves temperature functions. The right side of Equation (21) can be evaluated from charts developed by S. B. Gamble (Fig. 144). Temperatures t_{a_2} are plotted as ordinates, temperature differences $t_{a_1} - t_{a_2}$ as parameters, and values $1/c_a\gamma_a(t_{a_1} - t_{a_2})$ as abscissas. The latter are expressed in cu ft per min per kw (cfm per kw). Usually the units are so chosen that the left side of Equation (21) is expressed in Btu, and the volume in cu ft.

In order to use the abscissas from Figure 144 in Equation (21), the values are to be multiplied by $3413/60(= 56.9)$.

These figures are explained as follows:

$$\frac{\text{cu ft}}{\text{min} \times \text{kw}} = \frac{\text{cu ft} \times 60}{\text{hr} \times \text{kw}} = \frac{\text{cu ft}}{\text{Btu}}\frac{60}{3413}$$

Thus the readings in cfm/kw are to be multiplied by 56.9 to give the value in cu ft/Btu. The reciprocal of this value, multiplied by V_a, gives the right side of the equation.

Evaluation of the left side of Equation (21) should be based on the temperatures in the center and at the surface of the charge at the start and at the end of heating period. If the four temperatures do not differ greatly, the specific heat can be taken for the average of these four temperatures.

The method of plotting in Figure 144 is selected because, for very thin pieces with relatively greatly exposed surface, the law of heat content usually controls the heating process. In a first calculation the law of heat transfer in such cases need not be considered, and the chart may be used directly to find the necessary amount of recirculating air. The connected load is now determined from the useful heat and the wall losses. The amount of recirculating air is found from the chart as follows. From the temperature difference permissible in the charge at the end of the heating period, one of the curves is selected. If the difference is specified as 10 F ($\pm$5 F), the curve for 40–80 F should be selected, because the air must cover not only the useful heat but the heat losses as well.[60] The air exit temperature is read on the ordinate, and the value of *cfm/kw* on the abscissa. Multiplying *cfm/kw* with the value of the connected load gives the amount of air per minute which in turn determines the fan size.

[60] S. D. Gamble, *personal communication.*
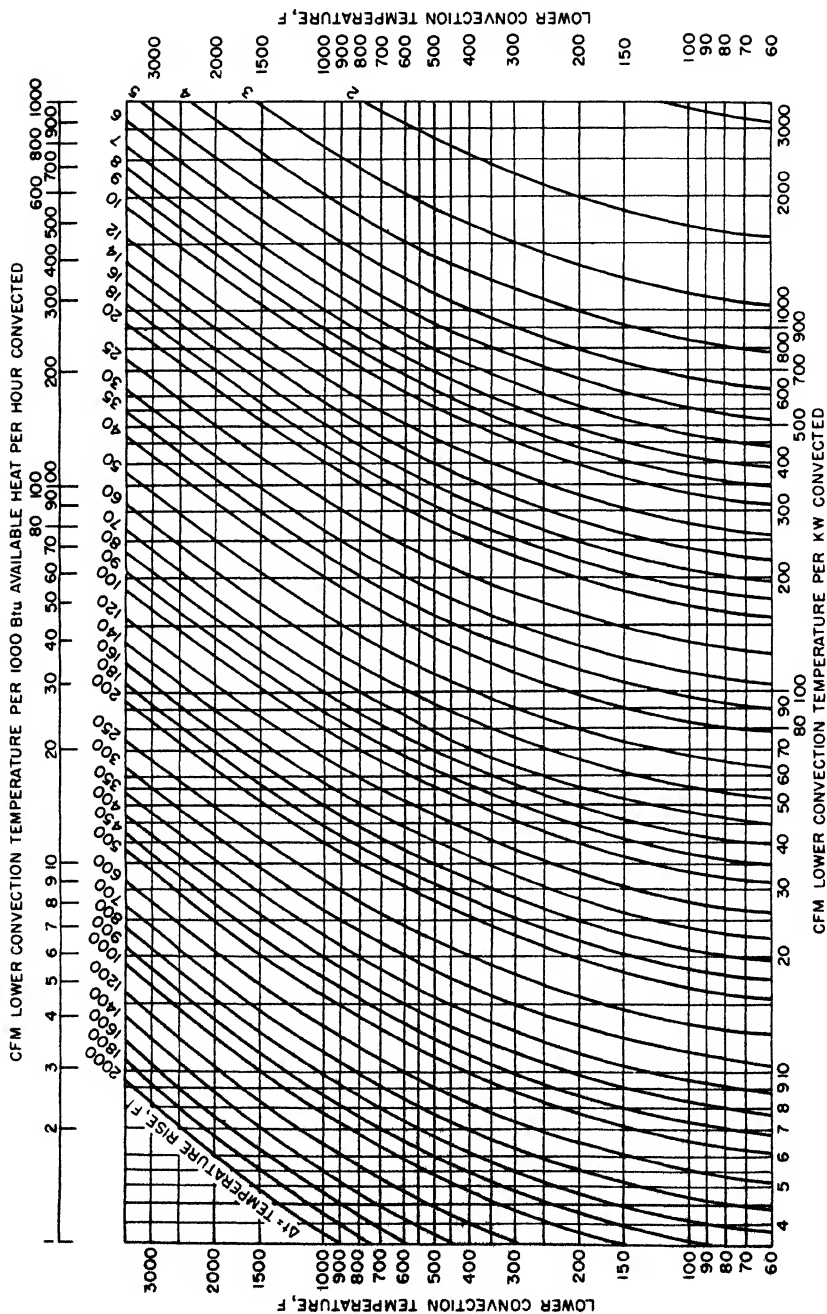
Fig. 144. Heat absorption chart. (Courtesy *Lindberg Engineering Company*.)

(c) *Calculation of Heat Transfer*

Calculation of heat transfer is based on the desired uniformity of the temperature distribution in the individual piece (see page 3). If the air is forced through a pile of material, the temperature differences in the individual piece may frequently be neglected. Then the temperature rise of the piece is described by:

$$\theta = 2.3 \frac{cw}{hA} \log \frac{t_a - t_c}{t_a - t_o} \tag{22}$$

Notation. Any consistent set of dimensions may be used, for example, those mentioned below.

θ = heating time, hr
c = specific heat of charge, Btu per lb, F
w = weight of charge, lb
A = surface area of charge exposed to air, sq ft
t_a = air temperature, F
t_c = mean charge temperature at time t, F
t_o = initial charge temperature, F
h = boundary conductance (air to charge), Btu per sq ft, hr, F

To solve Equation (22) and to use the graphs (page 9), the boundary conductance, h, must be known (see page 22).

C. CONDUCTION TYPE FURNACES

In this chapter, electrode salt bath furnaces and externally heated lead and salt baths are treated. The externally heated furnaces are in some ways a combination of radiation type and conduction type furnaces.

1. Electrode Salt Bath Furnaces

(a) *Introduction and Applications*

This type of furnace is probably the oldest resistance furnace ever used in industry. Originally the electrodes were suspended from the top near opposite sides of a ceramic crucible. The current in furnaces of this design usually passed through the immersed parts or tools. The latter, having very much higher conductivity than the salt, tended to overheat. In the next design developed, the current passes either from one electrode to the pot wall or to another electrode located fairly close to the first. This design is prevalent today. In the latest development, the electrodes are again located at two opposite walls, but instead of being suspended penetrate the pot wall. If the charge is kept away from the bottom and is not too long, no current passes through it.

Though electrode salt bath furnaces were originally built only for hardening purposes, the field of their application has grown considerably and is still increasing. Some of the more important applications may

be listed:

> Hardening of steel (carbon and alloy; direct and interrupted quench)
> Carburizing for case hardening of steel
> Cyanide hardening of steels
> Annealing for stress relieving of steel
> Tempering, including austempering of steel
> Annealing of copper, brass, and steels
> Annealing of aluminum and light alloys
> Age hardening
> Annealing of silver
> Heating for forging
> Brazing of steel, brass, copper, and aluminum alloys

(b) General Characteristics of Electrode Salt Bath Furnaces

Electrode salt bath furnaces have certain distinguishing characteristics which should be considered prior to selection and operation.

TABLE XV

DISTRIBUTION OF HEAT LOSSES

Temperature, F	Heat losses, kw/sq ft		Ratio
	From open surface	From insulated sidewalls	
1100	2.9	0.15	19.3
1350	5.0	0.19	26.3
1600	9.1	0.24	37.9
1850	15.2	0.28	54.0
2100	22	0.34	64.6
2350	31	0.39	79.3

First, there is the very unusual distribution of heat losses. In table XV typical heat losses from the top of the bath and from the sidewalls are compared. The wall losses per unit area depend on size of the pot and on thickness and quality of insulation; the losses from the bath surface depend on the surface temperature of the bath and also on possible ventilation and air movement over the surface. The losses from the bath surface can be greatly modified by a covering of carbon or slag. Obviously the surface area should be as small as possible, thus putting a premium on economic electrode design. Except for furnaces with electrodes penetrating the sidewall (page 186), only 70 to 85% of the total surface area of the bath is available for inserting load, 15 to 30% being used for the electrodes and their required adjacent space. Moreover well-fitting tight covers should be developed. Lacking these, processes involving protracted stay of the charge in the bath at elevated temperatures are only rarely advisable in salt bath furnaces.

Second, the influence of the properties of the bath on furnace operation should be considered.   Apart from the necessity of cleaning the pot when changing salts is the problem of the different electric resistivities of various salts.   Salts differ greatly in their resistivity, and in the degree of change of resistivity with temperature.   A furnace built for one salt, therefore, is not necessarily suited for another, unless the transformer is designed with sufficient taps for full power.

Third, the relationship of the salt to the charge is of interest.   Freezing of a layer of salt on a piece of metal when immersed prevents too rapid a temperature rise.   This layer must remelt, and because of the relatively low conductivity of solidified salt, the remelting takes some time to accomplish.   Only then does the heating progress rapidly.   This temporary freezing of salt (or lead) is the reason why even in immersion heating the ideal condition of "no boundary resistance" is not obtained in practice (see page 14).   A piece of metal withdrawn from the bath carries along with it some salt which often solidifies before the piece reaches the water or oil bath.   Thus the piece is protected against oxidation and an excessive temperature drop during the transfer to the quenching bath.   This protective salt layer is desirable provided (as frequently happens) it cracks off immediately upon immersion of the piece in the quench bath; otherwise the salt prevents rapid cooling and causes soft spots.   Obviously the salt carried out of the bath must be replaced, and heavy dragout adversely influences the economy of salt bath furnaces.

Finally, difficulties arise from the electrical insulating property of cold salt.   It is usually desirable to operate such furnaces continuously without shutdown, possibly lowering the temperature of the salt to just above the melting point during nonproductive hours.

(c) Starting Techniques

Cold salt does not conduct electricity at the voltages used in these furnaces (4–30 v); either in solid or in granulated form, salt is a poor heat conductor.   Hence, though electrode salt bath furnaces are usually operated continuously, provision must be made to start the furnace when cold. The salt may be premelted in a fuel-fired furnace and ladled into the electrode furnace, or a blow torch or acetylene burner may be used on the cold salt.   Molten salt runs easily into the spaces between the individual granules.   Therefore it is helpful to fill the pot only to such a height that the electrodes can be expected to take over a reasonable rate of energy supply.   In starting a furnace by blow torch, melting should begin near the electrodes, to permit the electrodes to assume the energy supply as early as possible, (i. e., as soon as sufficient salt is liquefied around the electrodes).

Also after the electrodes have taken over, difficulties may arise. A liquid pool may surround and connect all electrodes over their entire

length; but the salt at greater distance from the electrodes may be still solid.   Then the voltage must be cut down to avoid overheating the salt pool in the neighborhood of the electrodes.   Heating up can be greatly expedited by placing an arrangement of good conductors (such as steel

FIG. 145.   Heat conductors (*A*) for melting salt (heat flow in direction away from the electrodes shown by arrow *b*).

pipes or rods) into the bath before letting it freeze, or (with granular material) while putting the salt into the furnace.   These conductors carry away heat from a local salt pool and should be placed perpendicular to the plane of the electrodes (see Fig. 145).

A further step in the same direction is the insertion of starter resistors into the salt.   For this purpose the "conductors" mentioned in the preceding paragraph are connected to an external power supply, thus forming a resistance circuit.   Solid salt is practically a nonconductor.   But as it melts its resistance decreases, thus shunting the starter resistors increasingly.

Hence the voltage across the starter resistor should be decreased as the melting progresses.   The starter resistor can also be insulated electrically from the bath, thus eliminating the need for change of voltage. Standard immersion type resistors (see page 207) can be used for this purpose, provided they will withstand the temperature and the sheath material is resistant to the salt.   Some starter resistors should be as close to the electrode as possible.   Resistors if sufficient in number need not be placed perpendicular to the electrodes.   Also the starter resistor should be of such size and shape as to reach all parts of the bath, eliminating the necessity of heat conduction in extended stretches of solid salt.
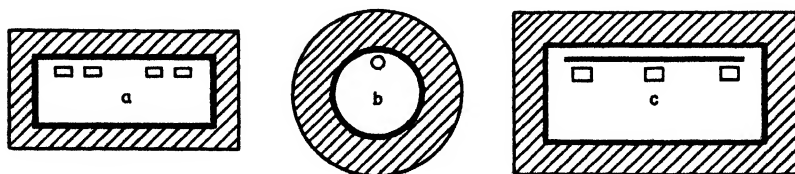
FIG. 146.   Electrode arrangement of electrode salt-bath furnaces.

Starter resistors located entirely near the bottom of the pot may be dangerous: the salt surrounding the resistor melts and expands and may burst the pot or erupt through a frozen crust on the top.   In one European design, a group of auxiliary electrodes swinging around a joint is placed on the solid salt.   A piece of carbon is pressed against them and is thus heated.   The hot carbon in turn melts the surrounding salt which

forms a gradually increasing pool, and melts the bath. Again a system of thermal conductors which can expedite melting to a considerable extent is advisable. Similarly, furnaces with closely spaced electrodes can be started by placing granulated graphite between adjacent electrodes.

(d) Furnaces with Closely Spaced Electrodes

DESIGN

Furnaces of this group include the Ajax-Hultgren furnace (Fig. 146a), with electrodes grouped in pairs and the electrodes of each pair separated by only a small column of salt. The high current densities in the salt column cause electromagnetic forces, which, in turn, result in a
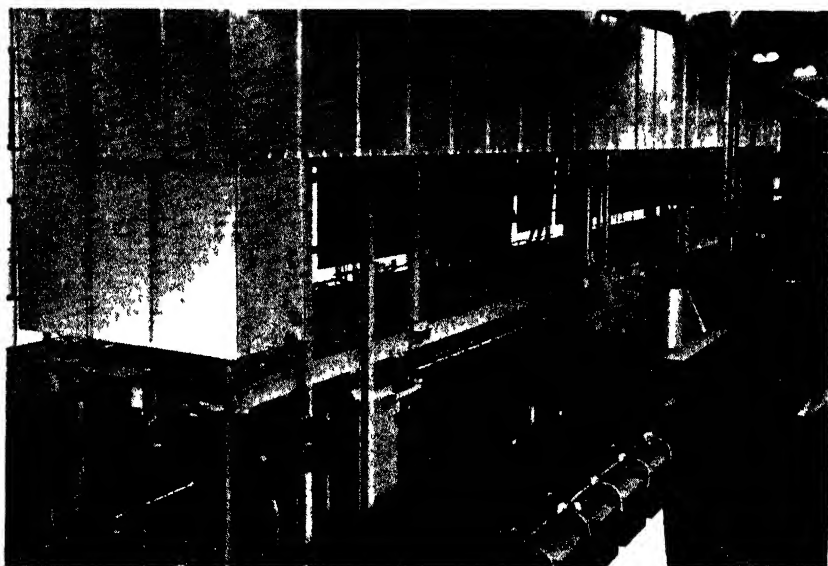
FIG. 147. Salt-bath furnace with conveying mechanism. (Courtesy *Ajax Electric Company, Inc.*)

turbulent flow of salt downward in vertical direction—opposite to the direction of flow that might be expected from natural convection: the density of the salt, decreasing with increasing temperature, causes the salt to flow upward as it is heated. In the Bellis Furnace, another design of this type (Fig. 146b), the current flows from one or two electrodes to the pot wall. The salt heated between the electrode and pot moves away because of differences in density. Figure 146c represents diagrammatically a third similar furnace. The current, instead of flowing from the electrode to the pot wall, flows to a collector plate, which is easily replaced.

Electrode salt bath furnaces have been built in impressive dimensions in combination with conveying mechanisms for continuous operation.

Generally the conveyors or other transport mechanisms are located outside the bath.   Figure 147 shows such an automatic furnace; the inside pot dimensions are 165″ long × 39″ wide × 39″ salt depth, connected load 500 kw, divided into three groups, separately controlled.   The furnace is used for hardening alloy tubes by the austempering method.

CALCULATION

Introduction.   The first steps of the calculations for salt bath furnaces follow the known calculation of other resistance furnaces.   Based on the desired output and the size of the pieces to be heated, the useful dimensions of the furnace are selected and the rate of "useful heat input" is determined.   Knowledge of the "useful dimensions" makes possible calculation of the heat losses: for the salt bath furnace, the space required for the electrodes should be estimated and the loss calculation is based on the actual dimensions rather than on the "useful dimensions."   When the rate of heat loss and the rate of useful heat have been computed, the connected load may be determined.

From this point, however, calculation for the electrode salt bath furnace differs materially from that of the common resistor furnaces. Determination of the dimensions of the electrodes present problems quite different from those of resistor design.

When reference is made to two electrodes, it should be understood that either two electrodes may be available, or the current may pass from one electrode to the wall of the pot, or the current can pass from the electrode to a collector plate placed in the bath.   For simplicity, however, the concept of two electrodes will be maintained.   The explanations refer similarly to the other designs, and the "two electrodes" are always to be understood as two metallic terminals of one current path in the salt.

From Figure 148 it is obvious that the following dimensions must be selected: depth of immersion, H; spacing of the electrodes, S; width of the electrode, D_e; and thickness of the electrode, B.   The terms "width" and "thickness" are not obvious.   Note the designation selected in Figure 148.

Selection of other dimensions, not marked by letters in Figure 148, is not discussed here.   For example, dimensions of the leads derive from calculations as shown beginning on page 136 in Volume I; see also page 81 in this volume.

Determining Factors.   In selecting dimensions of electrodes two objectives should be kept in mind.   (a) Energy dissipation should be uniform over the entire length of the electrode.   Provided the spacing of the electrodes is equal over their entire length the condition of uniform energy dissipation is tantamount to equal voltage between the two electrodes over the entire length.   This condition of course cannot exist, because the current flowing through any element of the electrode causes a

voltage drop. Thus the voltage at the top, E_1, is different from the voltage at the bottom, E_2. This ideal limit of constant voltage should be approached, however, as closely as possible. (b) The electrode itself should not contribute materially to the heating—the electrode should, in other words, not be an immersion resistor. Again, though complete achievement is impossible, the heat necessarily generated in the electrode should be kept at a minimum.
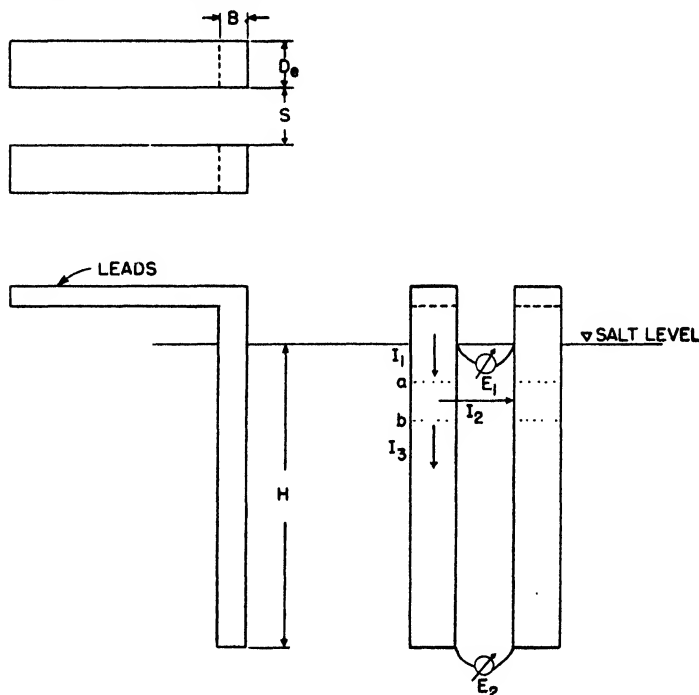
FIG. 148.   Dimensions of electrodes.

The first requirement—uniform heat generation—is related to temperature uniformity. Uniformity is greater if heat is uniformly generated. The second requirement—no heat generation in the electrode—is necessary for several reasons: temperature uniformity; the danger of excessive heat transport to the electrode leads if the electrodes are much hotter than the bath; and increasing electrode wear at the salt surface at higher electrode temperatures (if heat is generated *in* the electrodes, they will operate at higher temperatures than otherwise).

In salt bath furnaces, as in all heat-treating furnaces, a good temperature distribution in the empty furnace is very desirable; such uniformity though does not absolutely safeguard uniform heating of the charge, particularly in salt bath furnaces.

It is unavoidable that, after immersing a charge, the salt temperature in the immediate neighborhood of the charge drops as time passes. The temperature of the salt then rises, together with the temperature of the charge. An additional requirement for uniformity is that the charge should not form part of the electric circuit to any appreciable degree; otherwise a serious overheating of the charge, caused by great current density, is unavoidable, particularly at or near corners.

Uniformity of bath temperature without charge depends on uniformly generated heat in the salt between the electrodes and on efficient transfer, away from the electrodes into the entire bath, of the heat generated between the electrodes. Because of the fluidity of the salt the transfer of the heat away from the electrodes is accomplished mainly by movement of the heated salt itself and to only a limited degree by conduction of heat in the salt.

The problem of moving the salt away from between the electrodes to all parts of the bath depends on the design of the furnace. Some designers rely on circulation caused by thermal effects, others on circulation caused by electromagnetic effects. The salt may be distributed also by means of a propeller rotating in the bath. Moreover, the solution of this problem of circulating the salt depends on the arrangement of the electrodes with respect to each other and to the pot and therefore will not be treated in this book. The solution differs for various furnace designs. It should be remembered, however, that the matter of salt transport may also influence the relation of the dimensions, particularly the spacing, S. As will be explained, all dimensions are interrelated, and the selection is made by weighing the advantages and disadvantages of various combinations. The requirement for a certain spacing from the viewpoint of salt circulation does not obviate the following consideration, but rather renders the problem easier by reducing the number of possible choices.

Importance of Resistance Ratio. Both the ratio of voltages at the top and bottom of the electrode (E_1/E_2) and the ratio of heat produced in the electrodes to that produced in the salt are functions of the resistance ratio (R_s/R_e) where R_s is the resistance of the salt column and R_e the resistance of the electrode. With the notations as shown in Figure 148 and with ρ indicating the resistivity (subscript e for electrode, subscript s for salt) and with H for the total immersed length of the electrode, one can write the following two equations:

$$R_e = \rho_e H/BD_e \qquad (23)$$

$$R_s = \rho_s S/HB \qquad (24)$$

It can be shown that the ratio, E_1/E_2, is a function of the ratio, R_s/R_e. The proof can be established mathematically, or by setting up

an equivalent circuit and analyzing its characteristics.[61] Figure 149 shows E_1/E_2 as function of R_s/R_e. The resistance ratio is plotted on the abscissa axis and the voltage ratio on the ordinate axis. It can be seen that the voltage ratio increases from 1.018 for a resistance ratio of 300 to a voltage ratio of 1.27 for a resistance ratio of 1.67.

A voltage ratio of 1.018 indicates that at the top of the bath a voltage prevails 1.8% higher than that at the bottom. This causes energy transfer at the top approximately 3.6% higher than at the bottom, provided the change of

FIG. 149.   Voltage ratio in electrode salt-bath furnace.

resistivity of the salt with temperature is neglected.   Although the resistivity of salts changes with temperature very markedly, this simplifica-
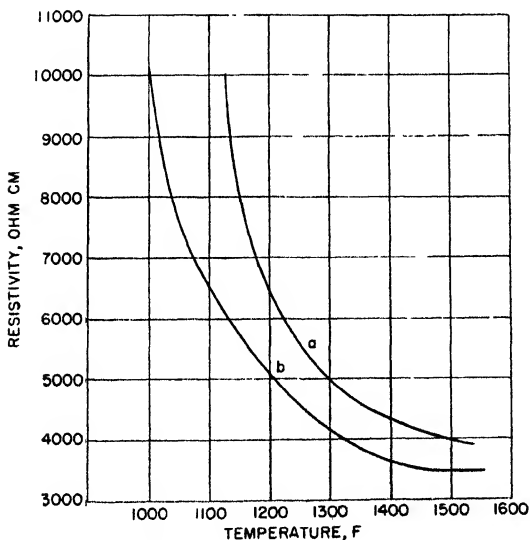
FIG. 150.   Resistivity curves of salt.

tion is permissible within narrow limits. What voltage ratio will be acceptable depends on design and judgment; certainly the ratio of 1.27 is impractical. Change of resistivity with temperature further aggravates existing differences; Figure 150 shows examples of temperature–resistivity curves for two different hardening salts.

The heat generation in the electrode is not uniform. From the salt level to the bottom of the electrode the current density drops steadily, because an increasing amount of current passes through the salt to the other electrode. For example, the current, I_1, passing through level a

[61] V. Paschkis, *Ind. Heating*, **9**, 1162 (1942).

(Fig. 148) splits: Part (I_2) flows to the other electrode and the balance $I_3 = I_1 - I_2$ flows through level b toward the bottom of the electrode. Since the voltage drop in the electrode is small, in first approximation the current may be assumed to drop from the full amount prevailing at the bath level proportional to the depth, and to be zero at the bottom of the electrode. This assumption is equivalent to neglecting the voltage drop in the electrode and assuming a constant voltage. By this assumption the ratio of energy liberated in the electrode, W_e, to the energy liberated in the salt, W_s, is given by:

$$W_e/W_s = 4R_e/3R_s \qquad (25)$$

This equation is found by writing the current, I, as function of the position, and integrating the I^2R_e curve. The simplification of assuming constant resistivity tends to reduce the ratio so that it will actually be smaller than that indicated by Equation (25).

Selection of Electrode Dimensions (only perpendicular current flow between the electrodes). The next question concerns the factors influencing the resistance ratio. Equations (23) and (24) may be combined:

$$R_s/R_e = \rho_s S D_e / \rho_e H^2 \qquad (26)$$

It is interesting that the thickness, B, of the electrodes has dropped out in this combination, indicating that neither voltage nor energy ratio can be influenced by changing B. This statement holds on condition that current flows only perpendicularly to the electrodes; the implications of this limitation are discussed below.

The value of B enters calculations in connection with the absolute value of the voltage between the electrodes, as shown in Equation (27), because R_s contains the value B (see Eq. 24).

$$W_s = \left(\frac{E_1 + E_2}{2} \right)^2 R_s \qquad (27)$$

where W_s represents the power generated between one pair of electrodes. In three-phase furnaces, voltage, power, and resistance are introduced according to the arrangement of the electrodes. Generally as high an electrode voltage as possible is desirable, because high voltages mean low currents and consequently smaller losses in the electrode leads and less expensive transformers.

There are, then, five variables (E, H, B, D_e, S), and only two equations (26 and 27) to correlate them. To use Equation (26), the maximum permissible voltage or energy ratio is selected. Thus from Figure 149 or Equation (25) the resistance ratio can be found. Even after this is accomplished, however, it is not necessarily possible to assign to each of the variables a definite magnitude.

The depth of immersion, H, can be either determined separately or related to the spacing. The total depth, T, from the salt level to the bottom of the pot is given. Some designers stipulate a given distance from the bottom of the electrode to the pot. It is better to relate the distance $(T - H)$ to the electrode spacing. If $T - H$ is too small, current will flow from one electrode through the salt and (when metallic pots are used) through the pot bottom to the other electrode. It is good practice to make the distance 2.5 to 3 times the electrode spacing:

$$T - H = (2.5 \text{ to } 3)S \tag{28}$$

Since T is known, H is definitely related to S, thus eliminating one of the five variables.

The voltage is now selected. Instead of working with E_1 and E_2, it is here probably sufficient to use $E_1 = E$ (as in Eq. 27). It must be recognized that this selection is tentative only. From E and Equation (27), R_s may be found, and from Equation (24), the ratio S/HB. Now select S and therewith H (see Eq. 28), and D_t follows from Equation (23). The selection of the spacing is subject to individual experience and to the exigencies of salt transport, particularly with electromagnetic stirring. S should in general be selected between $\frac{3}{4}$ or 1 in. and 2 to 3 in. The upper limit is selected because, if the spacing becomes too large, part of the salt surrounding the electrodes participates in the conduction of current and should therefore be left free of any part of the charge. This involves loss of costly space and waste of heat. If the spacing is too small, the furnace is too sensitive to minor inaccuracies in assembly and even a slight warpage of the electrodes results in substantial change of salt resistance and possibly even in a short circuit. Moreover the technique of salt circulation must be considered in connection with the spacing. If B is too small the voltage is decreased; if B is too high the voltage can be lowered. The width, D_e, should never be smaller than 1 in. and seldom exceeds 5 in. even for large furnaces.

Once S (and therefore H) is selected, and the desirable resistance ratio established, the width, D_e, follows from Equation (26). Of course the desired resistance ratio must have been established. From Figure 149 for example, a resistance ratio of $R_s/R_e = 200$ may be selected for a certain case. From Equation (25) it follows that in the electrode only 0.67% of the energy will be liberated, which is acceptable; now if, from Equation (26), D_e reaches an undesirable value, a different value of S has to be tried. For the thickness the limits are approximately the same as for the width (1 to 5 in.).

Equation (26) has, however, still another significance. For a given depth and spacing the resistance ratio is directly proportional to D_e/H^2. Thus, if for a particular case S and ρ_s/ρ_e are selected, Equation (26) may

be written:

$$R_s/R_e = C(D_e/H^2)$$
$$C = S(\rho_s/\rho_e) \tag{26a}$$

It follows from Equation (26a) that, if a width, D_e of an electrode has been found successful at one depth, it should be increased proportional to the square of the depth as the latter increases, if all other conditions are unchanged.

Example. If an electrode width of 1.5″ was successful with a depth of 12″, then for a 24″-depth (same electrode, salt, temperature, and spacing) the width should be increased to $1.5 \times 2^2 = 6″$. This width being too large, a different spacing and/or thickness should be tried.

For a greater depth of the bath, spacing S may be increased to avoid too low a voltage. Then the requirement of increased D_e is accordingly modified. A greater width than found by this rule is always permissible, and use of a greater width will increase the ratio of the resistances, R_s/R_e, thus providing for a lower voltage ratio, which is desirable.

It has been suggested that the electrodes be spaced not evenly, but rather closer together near the bottom and farther apart near the top. This arrangement seems rather complicated; moreover, as the electrodes wear off, the spacing changes nonuniformly.
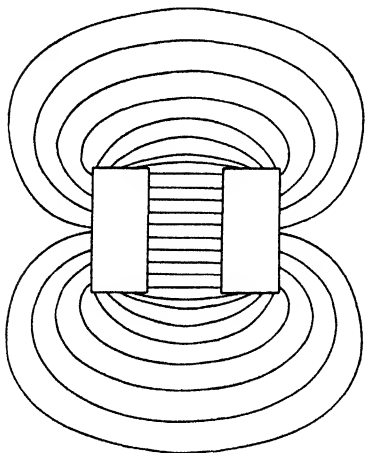
FIG. 151. Current flow around electrodes.

Irregular Current Flow Pattern. So far it has been assumed that the current flow from one electrode to the other is purely perpendicular to the surface of the electrode. Actually the flow pattern is very much more complex (Fig. 151). All flow lines except those between the electrodes and perpendicular to their surfaces have a greater length of path than the spacing, S. They act as a shunt to the salt column between the electrodes, or in other words, lower, for any given arrangement, the value of R_s below that found from Equation (24).

Although it is impossible at present to predict the flow pattern, the limits may be defined. These conveniently apply to the ratio of length of current path to the cross-sectional area, a ratio which, in heat problems, is sometimes called the shape factor (see Vol. I, page 43). This factor lies between two limits: the upper equals the ratio as used in the previous sections and prevails in straight parallel heat flow; the lower is based on

the concept that all current paths have the same length as the one between the electrodes and perpendicular to them.   Actually the corresponding S values are much larger, and this limit is thus never reached.   Flow patterns of this type have not been published.   Since the decrease of resistance is more marked for large spacing, small thickness, and large width, too great a distance between the electrodes should be avoided.

Because of this complicated flow the resistance of the salt column between the electrodes differs from that found by Equation (24).   The changed resistance may be accounted for in several ways.   A fictitious resistivity may be introduced; actually the flow pattern leaves the resistivity of the salt unchanged but adds to the current more paths of various lengths to the basic path, which extends from one electrode surface to the next.   The same correct resistance (i. e., including the many parallel paths) is obtained with the original geometry (length of current path S; area of current path BH) and a fictitious resistivity.   The latter, ρ_s', is not just a function of temperature and the chemical composition of the salt, as ρ_s had been, but, rather, changes also with B, D_e, and S.   Thus each time one or more of these three values changes, the calculation, and therefore the evaluation of Equations (24) to (26), changes.   No systematic investigation of this field pattern is known, so the influence of the electrode geometry on the apparent resistivity must be estimated.

The change of pattern does not, however, depend on the nature of the salt as long as the temperature difference of the salt between the electrodes and the outside is not large enough to change the resistivity substantially.   Any change that does occur helps decrease the effect of the "flow pattern" because the salt paths outside the electrode then not only are longer than the direct path of the electrodes, but lie in a zone of salt with higher resistivity.

(e) Furnaces with Widely Spaced Electrodes

DESIGN

Furnaces of this kind are always built with nonmetallic crucibles. The European design mentioned on page 173 is shown in Figure 152. Its main disadvantage is the danger of current passing through the charge. Since metals have a much higher conductivity than salt, the 'current crowds at corners or edges of the charge and thus tends to overheat them. To avoid this danger, the cross section of the bath must be large, resulting in high power consumption.   For these reasons, this design has been abandoned in the United States.

The Upton furnace (Fig. 153) represents a new and interesting concept in the design of salt bath furnaces.   The electrodes are inserted through the lower sections of the sidewalls and are water-cooled at their

outside end.   The electrodes are self-sealing; the salt escaping from the bath freezes on its way to the outside and prevents any more salt from flowing out.   By placing the electrodes at the bottom of the furnace, the current is limited to the lower section of the pot and is prevented from
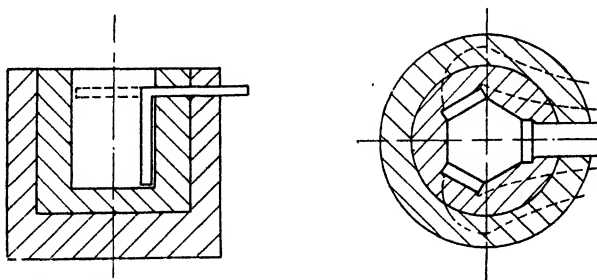
Fig. 152.   Salt-bath furnace with widely spaced electrodes—European design.

INSULATION BRICK

TILE

REFRACTORY CONCRETE

BOTTOM OF BATH

WATER-COOLED ELECTRODE

REFRACTORY BRICK
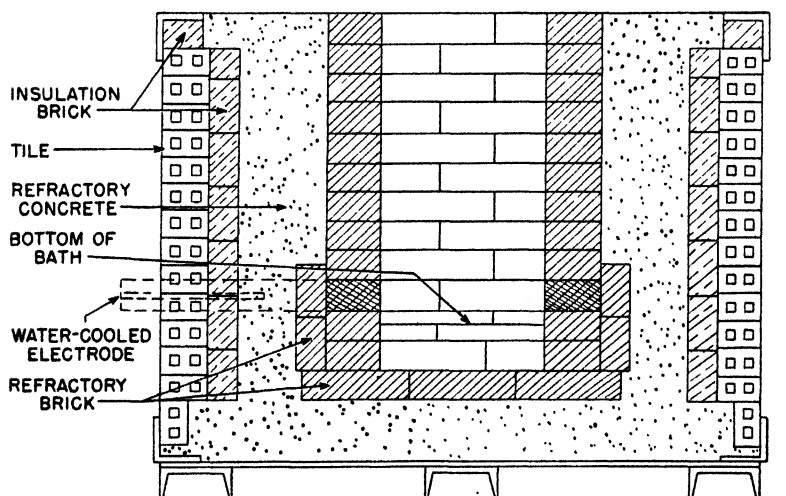
Fig. 153.   Salt-bath furnace with widely spaced electrodes.   (Courtesy *Upton Electric Furnace Division of Commerce Pattern and Foundry Company.*)

passing through the charge unless the latter is lowered too far.   The same furnace can be used with different depths of the bath, as long as a minimum depth, depending on the width of the bath, is maintained.   Temperature uniformity is achieved only by thermal circulation of the salt. Decarburization of the charge in high-temperature hardening (high-speed steels) is prevented by cleaning the salt through immersion of a graphite rod at intervals.   The advantage of this design is the gain in working space.   The entire surface area of the pot is usable for immersing work, without having to consider a safe distance from electrodes, etc.   The

absence of electrodes and connections at the top makes the operation easier and facilitates the application of conveying mechanisms and proper covers.

Baths of great depth have been built with this design. Reduction of the open bath area, made possible by the absence of electrodes, cannot be carried too far because of difficulties of removing sludge accumulating at the bottom. Disadvantages of this design include the difficulty of restarting a furnace if the bath should freeze (e. g., because of a power interruption) and the impossibility of replacing electrodes without bailing out the salt and installing a new lining. Electrodes have an increased life, compared with other designs, because of the reduced surface exposed to the salt, but can fail if a piece of steel should fall unnoticed into the bath.

CALCULATION

For this type of furnace calculation includes establishing correct voltage. Since transformers are equipped with a number of taps, high accuracy is not needed. The resistance depends on arrangement of the electrodes and on bath depth. Hexagonal baths with electrodes extending over the entire depth are frequently used in Europe. In such furnaces resistance is proportional to resistivity and inversely proportional to depth of the bath, but it is independent of the length of the side of the bath if each of the three electrodes covers, as is customary, one of the sides of the hexagonal cross section of the bath. Thickness of the electrodes is considered as explained above for furnaces with narrowly spaced electrodes.

In furnaces in which the electrodes are inserted near the bottom through the wall and cover only a fraction of the height of the sidewall (Upton type furnaces), the apparent resistance of the bath depends only on the resistivity of the salt and the exposed cross section of the electrode. Theoretically the depth of the bath has an influence; but rarely are baths sufficiently shallow to make this influence noticeable. For any height customarily encountered the resistance is the same, provided the exposed area of the electrode, the width of the furnace, and salt resistivity are unchanged. If the electrode area is A, the width of the bath D_b, and the resistivity of the salt ρ_s, the resistance of the salt column between the electrodes is:

$$R_s = \frac{1}{J} \rho_s \frac{D_b}{A} \tag{29}$$

where J is a factor allowing for shunting of the path by higher layers of salt (Fig. 154). The straight path of current is contained between lines 1 and 2. If the salt were no higher than D_b, then J would equal 1. But because of the salt in higher layers current paths 3, 3, etc. exist in parallel to those between 1 and 2, and thus the relationship $J > 1$ obtains.

2. Baths with Immersion Heaters

For low temperatures within the permissible range for immersion heaters (see page 207), the use of the latter is frequently preferable to electrode heating.

Resistors are usually placed on the bottom, and additional units sometimes also at the sidewalls. Immersion resistors can be used in baths for tinning, in oil baths, and in salt baths. The latter application is particularly important in connection with low-melting salts used for heating light metals and for tempering steels (Fig. 155). The resistors should have a large surface so that the temperature difference between surface and salt may be minimized. In some instances even finned resistor units have been employed to cut down this difference. The temperature limit is at present approximately 1100 or 1200 F. The ease of starting such furnaces (no difficulties arise through the high electric resistance of cold salt) makes this type of heating superior to electrode heating, when it can be applied.

Fig. 154. Current flow between electrodes in an Upton furnace.
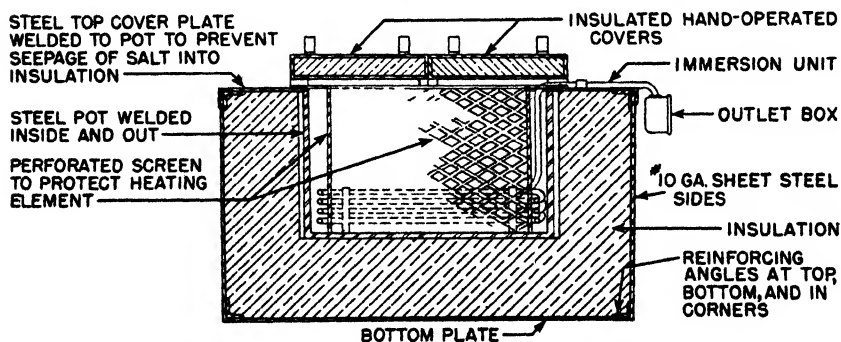
Fig. 155. Salt-bath with immersion heaters. (Courtesy *The A. F. Holden Company.*)

For large salt bath volumes, starting conductors (see page 176, Fig. 145) are helpful. The starting of large tin baths present no difficulties because the high thermal conductivity of the metal provides even temperature distribution.

3. Externally Heated Baths

(a) *Lead and Salt Baths*

For certain applications externally heated lead or salt baths are preferably used. At temperatures beyond the range of immersion heaters, lead baths cannot be used except in externally heated pots. Metals have so high an electric conductivity that they cannot be used in electrode type furnaces. Molten salts are sometimes used in externally heated pots, particularly if they are not in continuous operation. Externally heated lead and salt baths usually have round pots, because the extensive thermal stresses to which shapes other than round are subject limit the life of the pot.

INSULATED COVER
SEAL
ALLOY SUPPORTING RING
ALLOY POT
SOLDERLESS CONNECTOR
HEATING ELEMENT
REFRACTORY
DRAIN
INSULATION
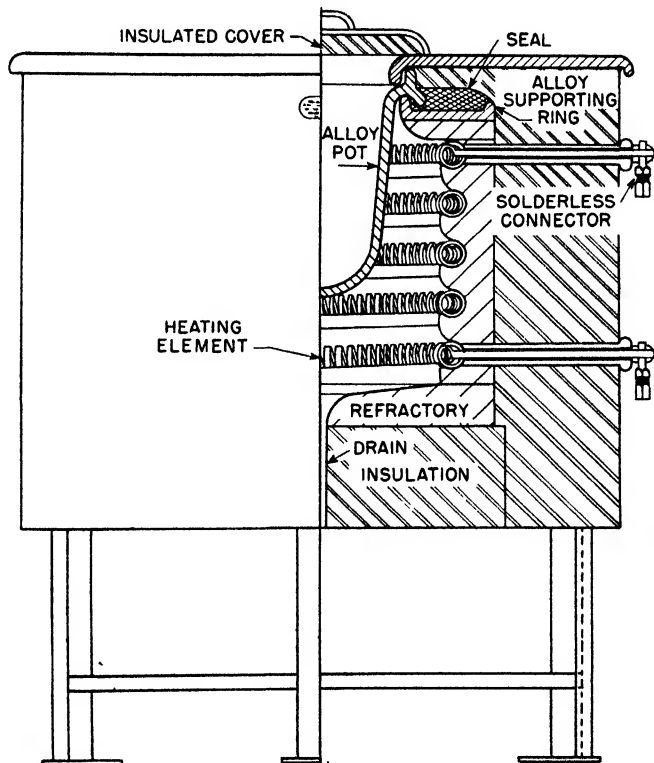
FIG. 156. Lead-bath furnace. (Courtesy *American Electric Furnace Co.*)

Externally heated lead and salt baths are actually a combination of radiation and conduction furnaces. The pot is located in the chamber of a pit furnace with resistors on the walls. The top plate of the furnace is provided with a collar which carries the pot and at the same time seals the furnace chamber against leaking salt (Fig. 156).

Pots in externally heated bath type furnaces have a very much shorter life than electrode furnaces operated at the same bath temperature

and with the same salt.   Oxidation in the furnace chamber in connection with the higher temperatures on the surface facing the resistors, and finally the mechanical stress of supporting the bath material from the flange, all contribute to this result.

The interaction of flange and collar is most important, because in withdrawing tools from the furnace, drops of salt or lead could easily get into the furnace chamber and there destroy the resistors, which, because of their high temperature, are quite sensitive to salt vapors.

Heating elements are placed only on the sidewalls, not on the bottom. The gain in heating area by heating the bottom would be small.   If the pot fails, the bottom resistors will be shorted by leaking bath material. In a leaking pot, side resistors are also in danger, but the spray of liquid may possibly not strike the resistors if the hydrostatic pressure is not too great.

Insulation and shell do not differ from those in pit type furnaces.

Lead baths offer no difficulties in starting up; also, externally heated salt baths can be started merely by switching on the power.   For pots of large diameter, melting of the salt usually takes a long time, which can be shortened by embedding bodies of high thermal conductivity (see page 176).

It is interesting to compare the method of heat transfer in a lead bath with that in an externally heated salt bath, and in the latter with an electrode salt bath.   If, in externally heated baths, the bath were entirely quiescent (which of course it is not), the heat transfer to a very large immersed piece would depend only on the thermal conductivity of the bath material, provided the time to achieve internal uniformity in the piece is quite long.   In such cases the heat would be transferred by conduction to the piece from the pot wall through the bath material, and the temporary drop of the bath temperature upon immersion of the piece would be relatively insignificant compared with the total heating time. The rate of heating increases with increasing thermal conductivity of the bath.   The thermal conductivity of lead is much higher than that of salts. Under more normal conditions, heating smaller pieces requiring shorter heating times, the piece absorbs heat from the immediately adjacent bath particles.   Here the determining property of the bath material is the thermal diffusivity—or thermal conductivity/(specific heat $\times$ density)—see page 55, Volume I).   The volumetric specific heat (density $\times$ specific heat) of salts and lead is of the same order of magnitude. Consequently the diffusivity of lead is higher than that of salts, thus explaining the faster heating of material in lead baths than in salt baths.

In electrode salt baths the heat transfer and the required temperature drop from the resistor to and through the pot wall are eliminated. Heat is transferred by convection—i.e. by moving salt particles.   The

advantage of the electrode salt bath is particularly felt where large quantities of material must be heated. In such cases the temperature drop from the resistors of externally heated pots to the bath become a major item.

(b) *Galvanizing Baths*

These operate well within the temperature range of immersion heaters (1100 F limit, galvanizing temperature 860 F). However, galvanizing kettles should not be heated by immersion heaters because zinc reacts readily with all metals known to be suitable for casings for immersion heaters. For example, the tendency of steel containers to react with zinc increases rapidly with temperature. The casing of the heater would of course have a higher temperature than the bath, and thus increase the danger of impurities in the molten metal when immersion heaters are used. The kettles stand on a bricked-up base in the furnace chamber, which is heated only on the sides, particularly at the upper parts (Fig. 157).

Iron (from the pot) going into solution in zinc forms an iron-zinc alloy, heavier than zinc and dropping to the bottom, from which it is removed regularly. Since stirring up this alloy would prevent proper galvanizing and cause attack of the pot walls, the bottom and the lower part of the sidewalls should not be heated. Because of the danger of contaminating the molten zinc, very uniform temperatures outside the pot in the furnace chamber are imperative to avoid hot spots on the pot wall.

As an example, the following figures are offered.[62] At 824 F, 32.6 mg per sq in. of iron go into solution; at 950 F, 130.4 mg per sq in.; whereas at 1076 F the amount is increased to 228.2 mg per sq in. The values of dissolution (mg per sq in.) are those obtained in 20 min, the rate of dissolution subsequently slowing down. After 1 hr dissolution is roughly 1.5 times that reached in 20 min. These figures were obtained in carefully controlled experiments and show the relative speed of reaction at different temperatures, rather than absolute values transferable to industrial zinc baths. The figures indicate that very accurate control of temperatures with time is necessary to avoid temporary overshooting of temperatures, and of control in several zones to prevent completely local overheating. The walls of the pit furnace in which the galvanizing kettle is located should be well insulated—not only because of lower power consumption but also because of the beneficial influence of well insulated walls on temperature uniformity in time.

Generally, covers cannot be applied to galvanizing baths because of the need of rapid immersion and withdrawal of material. Kettles for continuous galvanizing of wire, sheets, etc. are an exception. In such applications only a small part of the bath surface need be exposed

[62] K. Robertz, *Elektrowärme*, 9, 187 (1939). A. Buch, *ibid.*, 8, 98 (1938).

for introducing and withdrawing the charge, and the balance of the surface may be covered. Blankets of rock wool have been applied successfully.
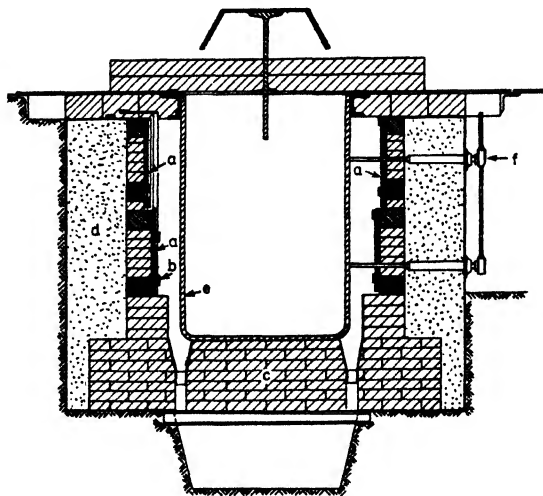
FIG. 157. Galvanizing kettle: *a*, resistors; *b*, refractory suspension bricks; *c*, refractory brick base; *d*, insulating powder; *e*, galvanizing kettle; *f*, leads for thermocouples.

Tin and oil baths, if not heated by immersion heaters, are built, similarly to galvanizing kettles, the difference being that bottom or side heat may be used.

Section Two: Direct-Heat Furnaces

Direct-heat furnaces are used in a number of electrochemical processes for heating nonmetallic materials, such as carbon (for graphitizing electrodes and other objects; for electrodes, see Volume I, page 120), silicon carbide, etc. There is probably no other group of furnaces the operation of which is based more on experience and skill, and no group which is mechanically simpler. The reason will be obvious from the following description. Direct-heat furnaces consist of a mass of nonmetallic material to be heated, placed on a more or less well insulated base, and surrounded by layers of thermal insulating, refractory material. Usually the charge is so arranged as to extend farther in one direction. At the two ends of the charge in this longitudinal direction, electrodes,

supplying current to the charge (Fig. 158), are connected by busses and cables to a variable voltage transformer.   Thermocouples permit observation of the temperature in various places.   The insulating material, selected so as not to react chemically with the charge with which it is in physical contact, serves not only to reduce heat losses but also to exclude oxidation of the charge by the air.
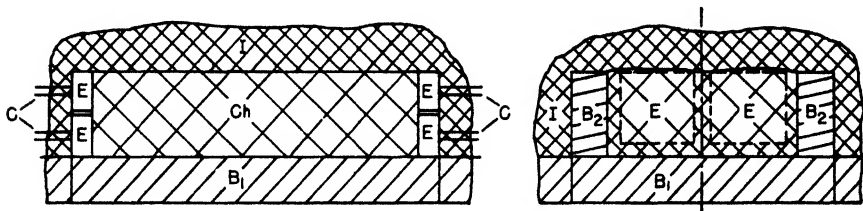
Fig. 158.   Schematic arrangement of direct-heat furnace: Ch, charge; B_1, brickwork base; B_2, brickwork sides; I, insulation; E, electrodes; C, connectors.

The furnace body is dismantled after each heat in order to allow withdrawal of the charge, and must be built up again before the starting of a new heat.   This crude arrangement requires an unusual reliance on the skill and experience of the operator.   Usually the charge, being in powder form, results in irregular placing of the charge which may cause contact difficulties with local sparking.

To obtain uniformly heated material from a direct-heat furnace, the charge should theoretically have uniform electric resistivity throughout, so that in each particle of the charge the same energy is liberated and all particles increase uniformly in temperature.   Thus, in the ideal direct-heat furnace no heat flow occurs.   Unfortunately, in practice, such furnaces are far from the ideal.   First, heat flow occurs toward and through the walls because there is no perfect heat insulation.   Second, slight unevenness in density or any irregularity in texture of the charge causes a local change of electric resistivity, hence a local irregularity (increase or decrease) of the rate of producing energy and therefore a change in temperature.   These local hot and cold spots cause heat flow which combines with the heat flow from the center of the charge toward its perimeter and the walls.   Most materials heated in direct-heat resistance furnaces have a marked dependence of electric resistivity on temperature and consequently the nonuniform temperature field causes additional irregularities in heat generation.   Conditions can either become increasingly worse, until the entire charge is spoiled, or can lead to a self-balance.

This brief explanation shows the importance of all measures that counteract uneven heat generation.

As mentioned above, a trend toward uneven temperature distribution can be attributed to two factors: one unavoidable (the heat loss to the surroundings through the insulation) and one avoidable (irregularities in electric resistance, caused by uneven packing, poor contacts, etc.). To avoid the latter, special care in placing the material in the furnace is necessary. To minimize the consequences of heat loss with the resulting uneven temperature distribution, more heat should be generated in the outside layer. A perfect uniformity of temperature rise could be reached only if all the heat necessary to cover the heat loss through the walls were generated directly on the surface. This would be the case if the mass were subjected to induction heat, in addition to the direct heat, or if the walls carried resistors which would raise the temperature of the walls at the same rate as that of the charge.

FIG. 159. Combined induction and direct resistance heat: induction coil (a) and external resistor (b) to cover heat losses; c, heat insulation; e, charge considered very long in direction d; no end effects.

Figure 159 illustrates this condition for a long furnace with no end effects in directions d or e. In the right half, an induction coil, a, faces the charge, e; in the left half, an external resistor, b, faces the charge, e, so that no heat flows from the charge to the outside insulation, c.

Since this way of covering the heat losses is unusual, temperature differences in the charge are unavoidable, even without local irregularities in the charge. This temperature difference can be calculated based on certain simplifying assumptions.

The ratio of center temperature to surface temperature is given by:

$$t_c/t_s = 1 + \frac{0.5}{m} \qquad (30)$$

where t_c and t_s are the center and surface temperatures of the charge, respectively, and m is the ratio of thermal resistance of the insulation to the internal thermal resistance of the charge from center to surface. Thus, if the thermal conductivity of the insulation is k_i (Btu per sq ft, hr, F), the thermal conductivity of the charge is k_c (Btu per ft, hr, F), and the distance from surface to center of the charge is L_c ft, the thickness of the insulation is L_i ft, then:

$$m = k_c L_i / k_i L_c \qquad (31)$$

This *m* is similar to the relative boundary resistance used in calculations of heating-up times (page 5).

Equation (30) holds under the following conditions: no end effects at the edges and corners; no change of electric resistivity and thermal conductivities of the charge with temperature; steady-state voltage decreased to cover only the heat losses, and to prevent further temperature increases; heat generation (watt cu in.) per unit volume uniform over the entire charge.

During the heating-up process the apparent resistance of the wall changes from an initial zero to the steady-state value. Thus the temperature difference between center and surface changes during the heating-up process. It will be small, even at early stages, if volumetric specific heat and conductivity of the wall material are low. By increasing the insulation—either in quality or in thickness—the value of *m* can be obtained almost as large as desired. Thus the degree of uniformity between center and surface may be increased as much as desired, but this uniformity is obtained in steady state only.

In these calculations constant thermal and electric properties have been assumed. Actually the frequent change of both properties with temperature complicates the problem and makes difficult any accurate calculation of the temperature distribution. However, determination by the electric analogy method is feasible.

Section Three: Appliances — Resistance Type

I. PURPOSE AND CLASSIFICATION

The distinction between furnaces and appliances is not definite but tentative definitions have been given on page 1. There are two reasons for using appliances rather than furnaces: sometimes heating occurs so fast that no insulated chamber is feasible or practicable; in other instances the appliance is combined with a production machine into a self-contained unit. Since the almost unlimited variety of appliances prohibits an exhaustive description, only the main laws of application and a systematic survey of types is presented.

Similarly to furnaces, resistance appliances also can be divided into *direct-heat* and *indirect-heat* types. In the former, the object is heated by placing it in an electric circuit. In the latter, resistors are applied, directly or indirectly, to the object to be heated and comprise a limited number of different types.

II. DIRECT-HEAT APPLIANCES

1. Application and Principle

Typical examples are the rivet heaters and the Snead machine for heating condenser tubes.   Moreover, all resistance welding devices belong to this group.   Because of their wide variety they are generally considered as a distinct group of machinery and are not discussed in this text.   Rivet heaters, direct-heat forging machines, and the tube heating machine mentioned above are all built on the same principle, schematically illustrated in Figure 160.   The piece is clamped between two electrodes connected to a low-voltage transformer, and the current is passed through the piece until it reaches the desired temperature.
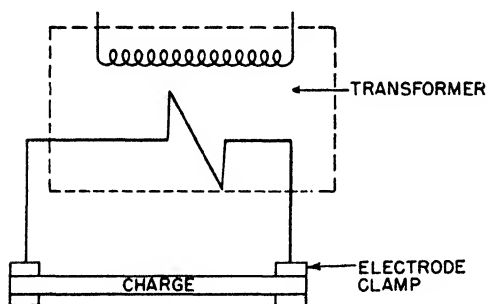
FIG. 160.   Principle of direct heat appliance.

For any given voltage the maximum temperature that can be reached by this method is determined by the heat losses.   At the maximum temperature the rate of heat supply equals the rate of radiation and convection losses (see page 263).   Practically, unless the voltage allows heating to a much higher temperature than that desired, heating is too slow and oxidizing occurs.   Also heat losses increase to an unacceptably high amount, if slow heating without insulation, as in appliances, is used.

Unless very high currents, which result in a marked skin effect, are used, heating occurs from the inside out.   Heat generation is, in first approximation, uniform, the approximation consisting in neglecting skin effect and temperature dependency of thermal properties.   But the surface is cooled by losing heat to the surrounding atmosphere.

The higher the voltage for a given cross section, the more uniform is the heating—again without considering skin effect and change of properties.   The piece heats so quickly that the relative heat loss is less important.   The skin effect—if not excessive—tends to make heating in such appliances uniform; more heat is generated where more heat is being used, namely, at the surface.

Heat generation, being proportional to the resistance, cannot be uniform if the resistance per unit length over the entire length of the current path is not uniform.   Changes in cross section along the path constitute one reason for such nonuniform resistance (see Fig. 161).   Parts of greater

cross section inserted between thinner parts require more heat (because of the greater mass), but generate less heat (because of the greater cross section) than adjacent parts.   The thicker sections receive heat only by conduction from adjacent thinner sections, an arrangement requiring relatively slow heating which as explained above is undesirable because of great heat losses and the danger of oxidiz-
ing.   Therefore, pieces of nonuniform cross section cannot be uniformly heated in direct-heat appliances.
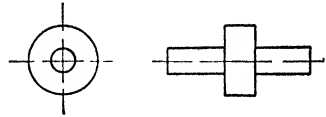
FIG. 161.   Piece of nonuniform cross section.

2. Contact Problems

In every direct-heat resistance appliance there are two zones where non-uniform resistance inevitably occurs—at the two contacts connecting the piece to the appliance.   Contacts or electrodes, then, present the greatest difficulty in the design.   The nonuniformity of the resistance is caused by the contact resistance between appliance and piece.   The parts of the piece adjacent to the contact tend to heat faster.   Fortunately there is an almost automatic countermeasure.   For various reasons the contacts are made of material with high electric as well as thermal conductivity.   For mechanical reasons the contacts are frequently quite heavy. The large cross section and high thermal conductivity permit the contacts to carry away by thermal conduction part of the extra heat generated in the contact zone.   Theoretically it is possible to calculate the contacts so that they carry away exactly the surplus heat, not more or less; then uniform heating over the entire length would occur.   Apart from the mathematical difficulties of this problem, to attempt a solution would not be practicable.   Little is known about the electric contact resistance. But, even worse, the heat from the piece must also traverse the "contact zone" and almost nothing is known about thermal contact resistance. Further, the contact resistance of a piece of given shape and size changes with its surface conditions.   A thin film of oil, specks of dirt, etc., by decreasing the area of contact, may cause serious trouble.   To some extent the contact resistance depends on the care with which the piece is placed in the electrodes before clamping them.

Thus design and dimensioning of the contacts must be done by trial and error to find the desirable balance between excess heat gain by contact resistance and excess heat drain by thermal conduction into the electric contacts.   That this balance is not easy to determine can be seen when rivet heaters are observed.   Rivets of the same size in the same machine heat sometimes from the head and sometimes from the bottom.

It is fortunate that in rivets the head, with its heavy section, is also a contact area; thus again the decreased heat generation (large cross

section) and the increased heat generation (contact resistance) counteract each other. It is usually good practice to make the contact pressure great. Springs and sometimes even hydraulic devices are used in addition to simple screw arrangements for smaller pieces. In some instances the contacts are water-cooled.

Notwithstanding the unsatisfactory condition in contact zones, direct-heat appliances find a useful place where the obtainable degree of uniformity is sufficient for the purpose, as with rivet heaters. The heating times are quite short and range (according to rivet size) from a few seconds to one or two minutes. The power consumption is in the order of magnitude of 0.20 kwhr per lb of steel.

III. INDIRECT-HEAT APPLIANCES (RESISTANCE TYPE)

A. APPLICATIONS

The uses for this type of appliance are almost unlimited.

Shoe Manufacture. Heat must be applied to the leather before and after polishing; heated irons may be of various shapes, some resembling the customary flatiron used for domestic purposes, some pointed or curved. The thread for sewing shoes is covered with pitch. Little containers of pitch, through which the thread passes, form an integral part of the shoe machine and are heated electrically.

Paper and Cardboard Manufacture. Machines for bending cardboard, and gluepots built into production machines, are heated electrically.

Newsprinting. Small containers for melting type metal are frequently heated electrically. Large kettles for melting the plates can be heated in the same way—the kettles are more truly melting furnaces but are customarily considered "appliances." The same is true for special drying fixtures for matrices used in printing.

Electrolytic Galvanizing Baths. If operated at elevated temperatures, the baths may be heated by electric immersion heaters.

Hot Water. Preparation is effected by heaters of the immersion type or by externally applied resistors.

Soldering and Branding Irons. The latter are used to mark livestock, wood, leather, or even metal.

Heaters to Defrost or Prevent Freezing of Railway Switches and Signals.

Commercial Drying Machines in Laundries.

Heaters for Curing Cereals in Grain Elevators.

In some instances—when space is at a premium, or for internal application of heat—the flexibility of the heating element or the smallness and flexibility of leads compared with fuel lines justify electric heat; at other times, the choice may prevent fumes or exhaust gases in the shop, or because special exhausts on machines are avoided. Some fields are the unquestioned domain of electric heat.

B. Principles

1. Survey of Problem

The principle of indirect heating by appliances is to transfer heat from a prefabricated resistor unit to solids, liquids, or gases. For solids the heater may need to fit into holes, or be applied to a plane or curved surface. For liquids the heater may be immersed in the liquid or surround wholly or in part a container or pipe carrying the liquid. Gases may be passed either over the surface of the resistors or through a heated tube.

Heaters have been developed which can satisfy the various above-mentioned cases and the relatively small number of basic types, which, properly applied, can fill these needs is remarkable.

The heat generated in the resistor wires must be transferred to the charge. Along its path, heat flow encounters resistances of various kinds, which may be classified as internal or external. Internal resistance comprises all thermal resistance from the wire to the enclosure of the heater, and external resistance all from the outside surface of the enclosure of the heater to the charge. Internal and external thermal resistance are "in series" (Fig. 162). Heat flow follows the same laws as electric current (Vol. I, page 20) and steady-state heat flow is therefore governed by Ohm's law:

$$t_1 - t_2 = q(R_i + R_e) \qquad (32)$$

Fig. 162. Thermal resistances in indirect-heat resistance type appliance: a, resistance wire; b, electric insulation; c, sheet metal protection; d, contact resistance (air space, etc.); e, heated object.

Here t_1 is the temperature of the wire, t_2 that of the charge, q the rate of heat flow, and R_i and R_e the internal and external thermal resistances, respectively. A high rate of heat flow, q, helps to obtain rapid heating. The maximum temperature, t_1, of nickel-chromium or other alloy wire is limited, partly because of the danger of oxidation by the air, always present in the heater to some extent, and partly because of the danger of melting at local hot spots. The temperature, t_2, of the charge is prescribed: a small internal and external thermal resistance apparently means increased permissible wattage.

The basic design problem to which nearly all others can be reduced may be described as reduction of the internal thermal resistance as far as possible, and at the same time application of the greatest possible cross section for the heater wire. The basic application problem is to reduce the external thermal resistance as much as possible.

2. Design Problems

The internal thermal resistance, R_i, is found in the insulation between wire and surface. Electrical insulation is necessary but automatically involves undesirable thermal insulation. Since every material which is a poor conductor of electricity is also a poor conductor of heat, the thickness of insulation must be reduced to the smallest safe value. Unfortunately the electric insulating value of such materials decreases with temperature, and the fairly high temperature of the wire necessitates rather thick insulation. Inasmuch as the value of insulation decreases also with voltage, appliances are mostly limited in voltage to 220 v, preferably 110 v. The need for mass production has restricted the manufacture for any lower nonstandardized voltage.

The heat flow from the heater wire to the surface encounters thermal resistance not only in the insulation; there is also a contact resistance between wire and insulation and between insulation and enclosure. If wire and insulation, or insulation and enclosure, are not in full contact this resistance may be in the form of heat transfer by radiation, or of lessened conductance. Increased resistances through the thermal contacts are dangerous in themselves. In addition, local increased resistance may cause local overheating. Since contact resistance is inversely proportional to the pressure of the surface across which heat flows, the manufacture of many heaters for appliances includes one step of compressing the entire element. Other heaters are manufactured by casting insulating cement around heater wires.

The outside shell or casing should be made of material which withstands the operating temperature and possible attack of the surrounding medium. For heaters which are to be used in certain molten metals, or in salts, steel casings are not sufficient; high operating temperatures in air may necessitate an outside casing of alloy steel rather than of soft steel. The surface must not only retain sufficient strength to hold the insulating material and wire, but should remain smooth to maintain good outside contact. It also must, of course, keep its shape (flat or round) for rigid units and remain flexible for heaters adapting themselves to the shape of the heated object.

Not within the domain of thermal resistance, but still part of the design problem, is the selection of wire dimensions (page 87). Any minute irregularity of the very thin wire usually employed may cause

fatal local over-heating—a danger lessened with increased cross section. Space requirements usually restrict the use of wire of heavy cross section. Flat wire should be so arranged that its flat surface is parallel to the heated face, and that the dimension perpendicular to the main direction of heat flow is as small as possible (Fig. 163).
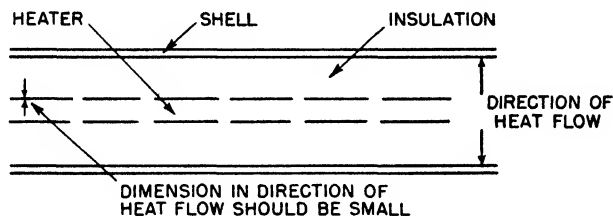
FIG. 163.   Flat wire—direction of heat flow.

In summary, the design problems of heaters for appliances include:

(*1*) Making the gage of the heater wire as heavy as practical.

(*2*) Selecting an insulating material with the highest thermal and lowest electrical conductivity possible.

(*3*) Selecting the insulation as thin as compatible with safety of operation at design voltage.

(*4*) Making all contact resistances as small as practical.

(*5*) Carefully avoiding local increase of contact resistance.

(*6*) Selecting material for the outside enclosure to resist the operating temperature of the heater and possible attack by the surrounding medium.

(*7*) Designing the surface to permit proper application with low external resistance.

3. Application Problem: External Thermal Resistance

The over-all external resistance depends on the charge, possible containers of the latter, and possible contact resistance between heater surface and surface of charge or container.   Shape, size, and nature of the charge should be considered in the same manner as in furnaces.

Sometimes the piece to be heated is so arranged in the heated appliance that temperature differences in the piece may be neglected.   Ordinarily, however, the relatively great thickness of the charge or the necessity of heating several pieces simultaneously does not permit such practice.   The contact resistance between the individual spaces are considered, and the heating time is calculated in the same manner as for furnaces.   (See page 3, and for discussion of contact resistance between pieces, page 25.)

Some appliances work with automatic temperature control and others without it. The latter operate largely with "constant rate of energy input" similar to induction heating, and uniformity should be calculated accordingly. When operating with automatic control, heating takes place with "constant temperature of the surrounding" (page 3). If the measuring device for the temperature control is on the surface of the load, the temperature of the heater is determined by the magnitude of the contact resistance in addition to the rate of energy input.

The boundary resistance between heater and charge though negligible in calculations for industrial furnaces, is more significant in electric appliances. The latter require containers, through which the charge is heated, or similar arrangements. In a hot plate, for example, heat must first be transmitted to, through, and from the plate: to the plate from the resistors, and from the plate to the object to be heated. Similarly, for a heated mold, the heat travels first from the resistor to the mold, through the mold, and finally to the material within.

The latter two steps, "through the container" and "from the container to the heated material," are often less important than the first, "from the heater to the container." The container is usually metallic and tends therefore to make uniform the heat received from the resistor and to store heat if there is temporary higher thermal resistance due to poor contact between container and charge. The contact resistance between the heater and the container is of greater importance.

Contact resistance between heater and container can be kept low by providing very smooth surfaces both on the heater and on the container, surfaces which do not change with time (no corrosion, etc.); by adapting the shapes of the surfaces to each other, and by applying sufficient pressure to secure good and permanent contact. If the heaters are not too long and are sufficiently rigid, bolts through holes at the ends may sometimes be used (Fig. 164). Often clamps or similar means to avoid separation of heater and surface are employed (Fig. 165).

Another way of providing for contact pressure is by using flexible heaters and providing external means of fastening; either separate spring or screwed-on clamps, or a knee lever on the heater itself (Fig. 166) may be provided.

For heating air and liquids, finned heaters (Fig. 167) provide a much greater area of heat transfer and therefore lower resistor temperatures. With heavy liquids such as tar, molasses, and heavy oils, the fins are not helpful unless combined with means to circulate the liquid. The main problem facing the designer in such cases is that of heat equalization in the liquid, rather than that of heat transfer from the heater. Sluggish heavy liquids have little or no convection and act almost like solids. Their thermal diffusivity being very low, the danger of local overheating

FIG. 164. Strip heater with ridges on side of base plate, providing rigidity; terminals on one end. (Courtesy *General Electric Company.*)
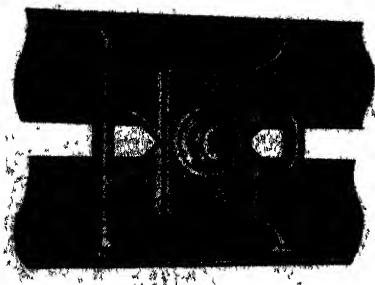
FIG. 165. Clamps for heaters. (Courtesy *Edwin L. Wiegand Company.*)
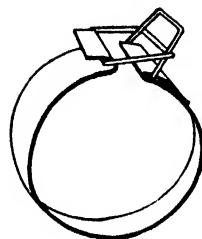
FIG. 166. Heater with knee lever tightening.

FIG. 167. Finned heater. (Courtesy *Westinghouse Electric and Manufacturing Company.*)

is great, without forced circulation. Even with forced circulation, stagnant pockets of the liquid may still possibly adhere to the heaters, thus creating overheating.

C. TYPES OF HEATERS

It is not within the scope of this book to show all available types of heaters and therefore only a few examples will be discussed.

1. Rod Type Resistors

The rod type resistors, in round or triangular cross section, come in various forms. One of the basic forms has a terminal on either end (Fig. 168). In one method of manufacture the heater consists of a helical coil of nickel-chromium wire placed in magnesium oxide powder. The
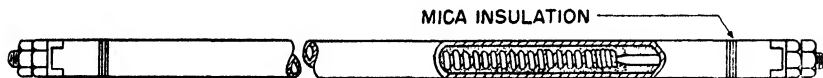
MICA INSULATION

FIG. 168.   Rod type resistor.   (Courtesy *General Electric Company*.)

latter serves as electric insulation between the resistor wire and the outside protective metal casing, made, according to temperature and nature of surrounding medium, of copper, steel, nickel-plated steel, chromium steel, or nickel-chromium. The resistor coil having been properly centered and the magnesium oxide filled in, the assembly is subjected to a sledge hammer and thus stretched. The insulators thus become very dense and of almost rocklike texture. Terminals are made by inserting a rod in the coil; the outside ends of the rods are threaded and provided with nuts, between which the connections of the cables are placed.

Another manufacturing process consists in compressing the tube, into which resistor coil and insulation have been filled, in a hydraulic press, and firing the unit to cure the insulation. The cross section of rods manufactured by this process is approximately triangular.

Round, as well as triangular rod type resistors, if bent so that both ends of the heater are on one side (U-shaped), allow the heaters to be immersed in liquid with the ends extending out of the bath. In order to have greater exposed surface and to bridge the sidewall, several bends can be applied to the heater proper, resulting in complicated shapes (Fig. 169).

Some types of resistor rods may be cast into gray iron. The cast-in unit, suitable for immersion into metals or fluids which do not attack cast iron (therefore not usable in zinc), results in a rugged heater with appreciable heat storage (Fig. 170).

2. Flat Heaters

A second basic type of heater—as distinguished from the "rod type units"—are flat heaters. Figure 164 shows one such heater in rectangular form, Figure 171 some of the special shapes made on the basis of flat heaters (see also Fig. 172). Figure 167 shows a finned heater which may also be bent, possibly to form a complete ring. The ring and segment units are useful for local application of heat (Fig. 172). The heaters are somewhat resilient and therefore provide good contact. Springs or
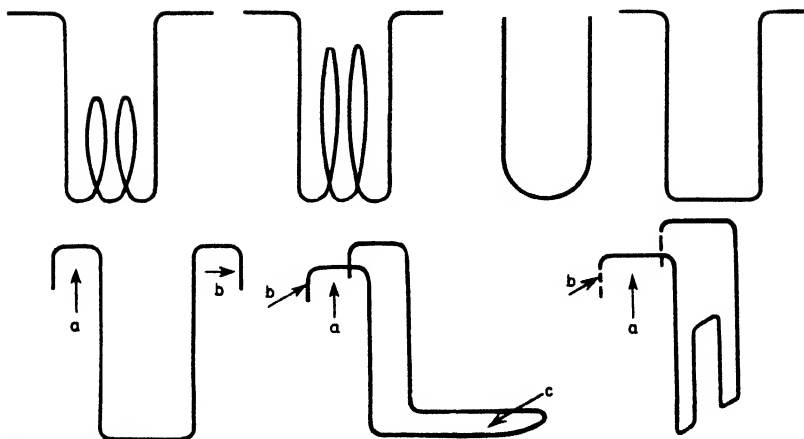
FIG 169. Examples of bent rod type resistors. *a*, space for the furnace wall. *b*, downward arm, sometimes applied, *c*, one or several loops
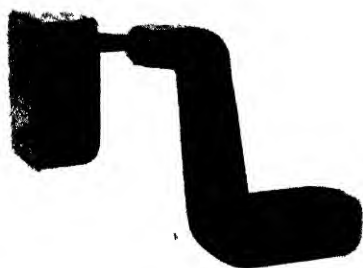
FIG 170. Cast-in rod type resistor. (Courtesy *General Electric Company*.)
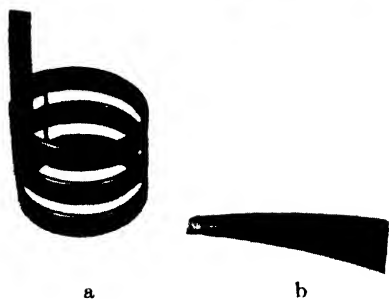
FIG. 171. Types of flat heaters. (Courtesy *Edwin L. Wiegand Company*.)

FIG. 172. Strip heaters. (Courtesy *Edwin L. Wiegand Company*.)
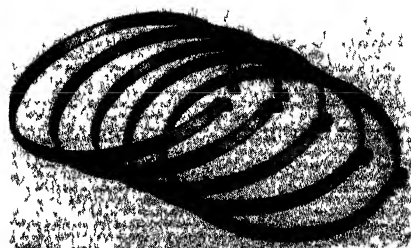
knee lever action may be employed in assembling.   Some designs provide
screwed-on clamps (Fig. 165) spaced possibly at 5″ intervals.

3. Other Types

For heat application in small holes, cartridge heaters are convenient
(Fig. 173).   The sheath may be made of copper, brass, steel, or stainless
steel, permitting surface temperatures up to 1200 F.   The coiled resist-
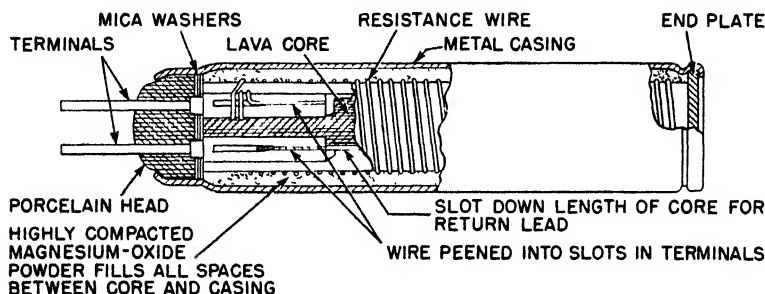
Fig. 173.   Cartridge heater.   (Courtesy *General Electric Company.*)

ance wire is wound around a ceramic core and insulated from the casing.
The return lead is brought out through the hollow core, so that both
terminals are on one side, or terminals at both ends may be provided.

A type of heater used in some appliances, although not generally on
the market as separate heater unit, consists of a mica strip over which a
very thin flat nickel-chromium wire is wound.   Additional mica sheets on
either side cover the wire and insulate it from any enclosure into which
it may be put.   These heaters, because of their constitution, are limited
to uses at low temperatures and with small intermittency.

Mention should finally be made of heating cables, having a nickel-
chromium wire, asbestos insulation, and a lead sheath.   The permissible
surface load is approximately 2 to 2.5 w per sq in. of surface area; the
maximum permissible sheath temperature is 150 to 180 F.   The cables
have wide application, and their mechanical flexibility permits easy
installation.

D.   Typical Applications of Appliances

Soldering Iron.   In the most common type of iron, the soldering tip
fits relatively loosely into an annular heater and is held in position by a
set screw (Fig. 174).   As the tip oxidizes and oxide accumulates between
heater and tip, the heat transfer becomes poorer.   For small portable
irons a good heat transfer from the heater to the tip is difficult to obtain,
and, since weight limitations do not allow automatic control, the iron if
used intermittently may get very hot.   A finned stand would hold the
iron while heated but unused; the great surface area of the stand cools

the surface effectively during intervals between soldering.

Containers with Water Bath. When heating, cooling, or melting materials at greatly changing output, uniformity is enhanced by heating a water jacket (Fig. 175) surrounding the container for the charge. The water forms effective heat storage and absorbs excess input during the period of reduced output.

Heating of Plates. Cartridge heaters for plates (Fig. 176) expand in service and should fit the heater hole as snugly as possible. A tool inserted through a small hole through the balance of the plate thickness, can push the heater out. A disc inserted at the bottom of the hole avoids damaging the bottom of the heater.
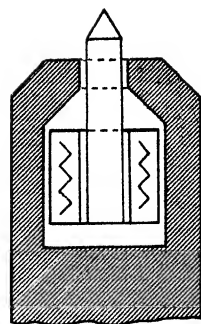
FIG. 174. Soldering iron.
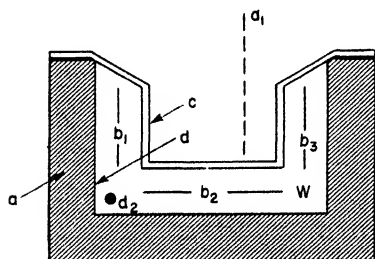
FIG. 175. Heating through water bath: *a*, insulation; $b_1 \cdots b_3$ heaters; *c*, pot or container for charge; d_1, d_2, optional positions for temperature control; *W*, water bath. Heaters $b_1 \cdots b_3$ can be immersion heaters or fastened to the inside wall (*d*) of the insulation. According to input rating, all or only some of the units are needed.

CARTRIDGE HEATING UNIT

DISC AT BOTTOM OF HOLE

DRILL HOLE SAME DIAMETER AS LISTED DIAMETER OF CARTRIDGE UNIT HEATER IS FURNISHED SLIGHTLY UNDERSIZE TO PROVIDE A SNUG FIT

FLEXIBLE CONDUIT

SQUEEZE CONNECTOR

HOLE TO FACILITATE REMOVAL OF HEATER

FOR LARGE-SIZED CARTRIDGE UNITS, USE A REDUCING BUSHING
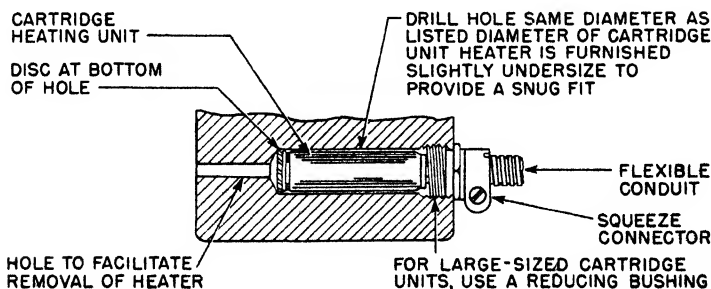
FIG. 176. Arrangement of cartridge heater in plate. (Courtesy *Westinghouse Electric and Manufacturing Company.*)

Heating of Rotating Rolls is made possible by inserting a heater into the hollow roll and supplying current by slip (commutator) rings (Fig. 177).

Immersion Heaters. They may be used in pipes for circulating a heating fluid—oil, water—through the pipe and to a heat absorbing container, and returning through the pipe. It may also be used for heating a fluid in continuous flow, *e. g.*, to keep oil in a fuel line at a desirable degree of viscosity (Fig. 178).
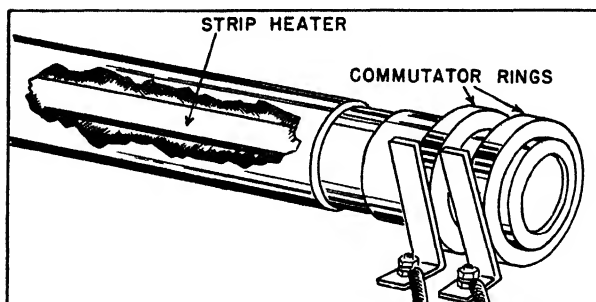
Fig 177 Heating of hollow roll (Courtesy *Edwin L Wiegand Company*)

Air Heating   Air-heating units are preferably finned, and may consist of several turns of a finned heater (Fig 179)   Placing one or more such heaters in a shell and forcing air axially through and across the heater provides a simple and efficient air heater
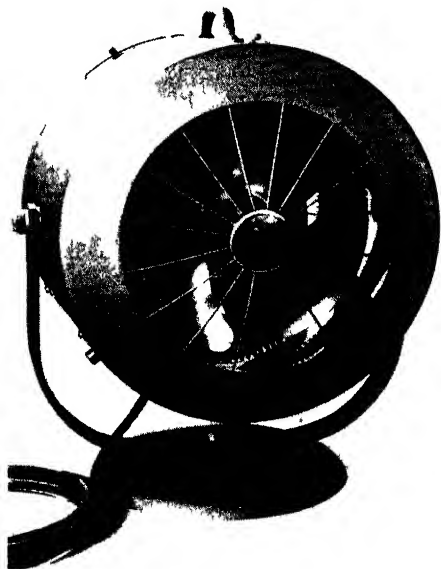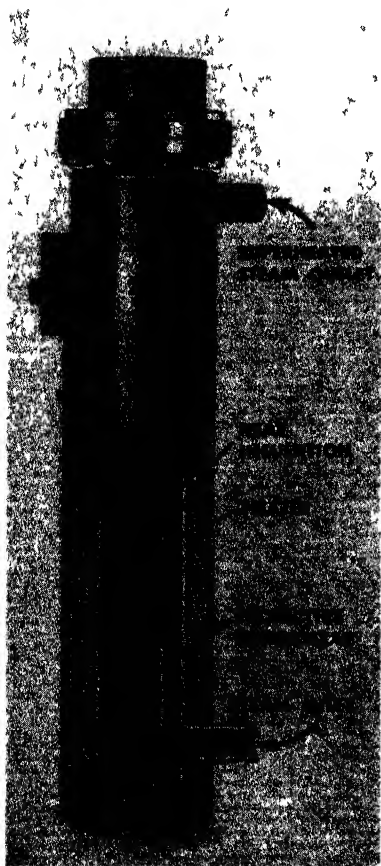
Fig 179. Air heating by bent finned heater   (Courtesy *Westinghouse Electric and Manufacturing Company.*)

← Fig. 178   Pipe immersion heater. (Courtesy *Edwin L Wiegand Company.*)

CHAPTER FOUR

Induction and High-Frequency
Capacitance Heating

I. INTRODUCTION

A. ELECTRICAL ASPECTS

Induction heating and high-frequency capacitance heating (HFC) are frequently considered related and in fact sometimes are erroneously confused. Electrically as well as thermally, the two procedures are entirely different, the only common link being the use of similar power supply systems.

Induction heating can be applied only to electric conductors, whereas HFC heating can be applied only to electric insulators. Induction heating may be considered electrically a transformer problem, HFC heating a condenser problem.

An alternating current passed through a coil surrounding a ring, induces an alternating current of the same frequency in the ring (Fig. 180). If the coil and the ring jointly are surrounded by a "core" of magnetic material, for example certain types of steel (Fig. 181), the familiar diagram of a transformer is obtained.

If the ring in Figure 180 is replaced by a solid cylinder, this cylinder can be considered as being composed of a number of concentric rings, and the conception of a transformer can still be maintained. In the core type arrangement, heating of a solid cylinder would not be possible. The load must always be in the form of a loop or ring, to permit insertion of the core. The core improves the coupling between the "primary" coil and the "secondary" ring, although it can be eliminated, with some loss in efficiency.

Intermediate solutions, with a core provided for a part of the magnetic path, have been used, particularly in heating problems (see Fig. 182). Figures 180 and 181 are schematic illustrations for the two big groups of induction heating equipment: core type and coreless equipment. The core decreases the resistance for the magnetic flux. Generally, the higher the frequency in the system, the more readily the core can be abandoned.
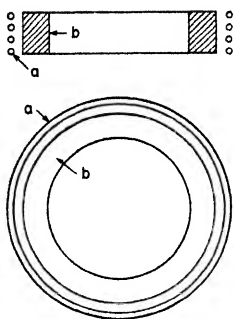
FIG. 180. Principle of in-
duction heating without core:
a, coil; b, charge.
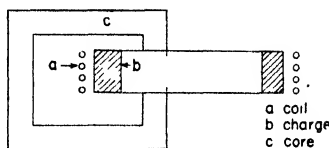
FIG. 181.   Principle of induction heating
with core transformer.
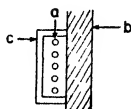
FIG. 182.   Induction
heating with part core.

FIG. 183.   Principle of
high-frequency capacitance
heating: a, slab of insulating
material, b, electrodes

Except for some special ar-
rangements, cores are con-
sidered necessary at fre-
quencies below 100 cycles
per second, and may be omitted at higher frequencies.   Heating ap-
pliances as well as melting furnaces can be subdivided into core type
and coreless equipment.

Although the basic concept of the transformer is applicable, rational
analysis of the electric phenomena of induction heating, particularly in
high-frequency heating, is limited to relatively simple cases.

HFC heating may be understood from the working of an electric
condenser, being based on the losses in a condenser.   In general practice,
of course, the losses of a condenser should be minimized; in HFC heating
the losses of the "condenser" produce the desired thermal effect, and
should therefore be as high as possible.   These conditions are opposite
to those in induction heating, where the losses in the "transformer" should
be as low as possible.

It may be well to describe in simple terms the working of a condenser.
In its simplest form, a condenser consists of a "dielectric" or insulating
material placed between two conducting electrodes (see Fig. 183).   The
following remarks hold for an infinitely large slab; Figure 183 may
be considered as one part of the condenser, cut out of the middle of the
infinite slab.   Consider first a d-c condenser.   If a d-c potential of E
volts is imposed on the electrodes, the plate absorbs a certain amount of
energy, expressed, for example, in ampere-seconds, or coulombs.   A plate
of a different material or different thickness exposed to the same potential
absorbs a different amount of coulombs.   Thus, the ability to absorb a
given amount of coulombs, if exposed to a definite voltage, is a property
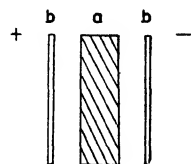
of the arrangement, and is called capacitance, C, which is related to voltage, E, and stored coulombs, Q, by:

$$C = Q/E \qquad (33)$$

When loading the condenser with Q coulombs, the electrons of the "dielectric" are displaced, and this displacement is accompanied by a current in the dielectric, which is called the "displacement current." Now suppose that the polarity of the electrodes in Figure 183 is changed after the plate has been loaded to "saturation" or to steady state. Then a new displacement of electrons accompanied by a current of displacement occurs. With alternating current such changes of polarity occur rapidly —at the "frequency" of the current. Consequently displacement currents flow uninterruptedly, changing their direction with the frequency of the impressed voltage, but in each direction causing a heating of the material. This heating effect is used in the HFC heating. "High-frequency capacitance" heating derives its name from the fact that it occurs only if there is a capacitance arrangement available, that is, a material with high resistivity and sufficiently high dielectric strength exposed to an electric voltage brought to it by means of two conducting electrodes. This method of heating is also frequently called dielectric heating, because the heating effect takes place in the "dielectric." In a condenser connected to a d-c supply (Fig. 184) the current changes with time. Resistors slow down rate of current change sufficiently to permit reading of an ammeter. The current-time curves, shown in Fig. 185, are different if different values of resistors are

Fig. 184. Direct-current condensers.

used. But the area under each curve (which area has the dimension of ampere-seconds or coulombs, if current were plotted in amperes and time in seconds) is constant for a given condenser and independent of the resistor used. This d-c current, then, is the same as the current of displacement. In discharging the condenser a similar current with reversed polarity is obtained.

The displacement current is not identical with the current that might be read on an a-c ammeter, inserted in an a-c circuit (Fig. 186). In fact, if materials with increasingly lower dielectric losses were used, until finally a material were found which has no losses, the alternating current would hardly change. The current, absorbed by such an ideal condenser, leads in phase 90 degrees as against the voltage. This may be verified by measuring voltage, watts, and current (Fig. 187a). For practical condensers the current is slightly larger than in the ideal condenser, but the phase angle is now less than 90 degrees (Fig. 187b). The small part of
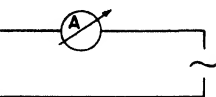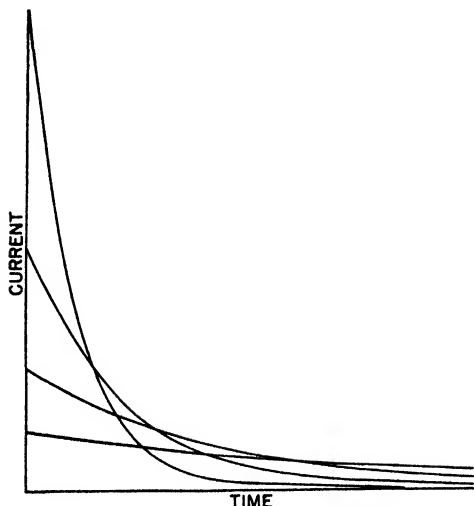
FIG. 186.   Alternating
current condenser.

CURRENT

TIME

FIG. 185.   Schematic current–time
curves for condensers.

the current which is in phase with the voltage represents the displacement current and causes the losses in a condenser and the heating effect in dielectric heating.   For HFC heating a large power factor, or phase angle, is desirable, for condensers a small one.
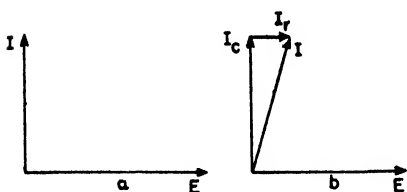
FIG. 187.   Vector diagrams for condensers: (a) ideal condenser; voltage E and current I at 90 degree angle; (b) actual condenser; E and I at less than 90 degree angle. I has two components: I_c, capacitive component, leading 90 degrees, and I_r, ohmic component, in phase with voltage.

B.   THERMAL ASPECTS

Also with respect to thermal phenomena, induction and high-frequency capacitance heating are entirely different.   The only feature common to both is the generation of heat within the body.   However, in induction heating, this heat generation is always localized, whereas in HFC heating the generation of heat may be uniform.   In induction heating, then, uniformity of temperature in the piece can be obtained only by heat conduction; in HFC heating, heat conduction usually is the greatest factor causing temperature nonuniformity.   The thermal differences between the two methods can be understood from the Figures 188 to 190.

Figure 188 illustrates two slabs of such great dimensions that end and corner effects need not be considered.   Only half the thickness of each slab is shown, that is, the distance from one surface to the center plane.

The amount of shading indicates the strength of the "heat source." In induction heating (Fig. 188a), heat generation is very strong at the surface and decreases toward the center: the heat source is "strong" at the surface and weakens toward the center. The rate of decrease depends on the material to be heated and the frequency applied, and is allied with the "skin effect" (see page 221). In HFC heating (Fig. 188b), heat generation is uniform throughout the slab.

Figure 189 shows two schematic energy balances for layers Δa near the center of the slabs. In induction heating (Fig. 189a), heat is being received by layer Δa through conduction from layer Δb;
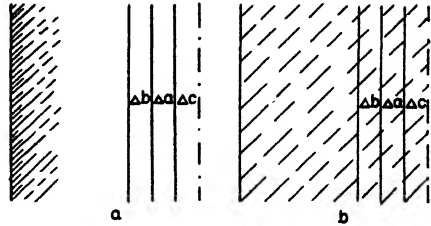
FIG. 188. Thermal principles for induction (a) and high-frequency capacitance (b) heating.

this heat is used in part to raise the temperature of layer Δa and is partly passed on to layer Δc by thermal conduction. In HFC heating, heat in layer Δa (Fig. 189b) is in part received from layer Δc by conduction, and a portion is generated in layer Δa. The heat in layer a is partly used to raise its temperature and is partly conducted to layer Δb. Near the
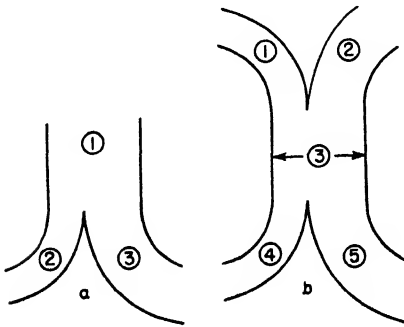
FIG. 189. Energy balance for layer Δa. (a) Induction heating: (1) heat received by thermal conduction from layer Δb; (2) heat used for raising temperature of layer Δa; (3) heat conducted to layer Δc. (b) High-frequency capacitance heating: (1) heat received by thermal conduction from layer Δc; (2) heat generated in layer Δa; (3) total heat in layer Δa; (4) heat used for raising temperature in layer Δa; (5) heat conducted to layer Δb.

surface of the slab, within the depth of penetration, the pattern in induction heating is similar to that shown in Figure 189b, with the difference, however, that any layer (Δa) would receive heat (1) by conduction from layer Δb and pass it on (5) to layer Δc. The widths of various streams of heat vary with time, by change of thermal and electric properties with the momentary values of temperatures. Finally, Figure 190 shows the temperature distribution in the slabs at different times after start of heating. Curves a refer to an early time, soon after start of heating. In induction heating (Fig. 190a), the center is still practically cold. The highest temperature occurs just below the surface.

(The distance from the surface to the maximum is exaggerated in the figure.)   The small temperature drop from the maximum to the surface

is caused by heat losses to the surroundings.   At very much later times, *b*, the temperature throughout the slab is almost uniform for induction heating.   All the heat generated is lost to the surrounding. From the point of highest temperature, heat has penetrated to the inside of the slab and has raised its temperature to the almost uniform value shown in the figure.   After

Fig. 190.   Temperature distribution in slabs.

an infinitely long time, the temperature would be perfectly constant from the center to the point of heat generation.

For HFC heating (Fig. 190b), conditions are different.   At early times (curve *a*), temperature differences are much smaller than for induction heating.   Heat generation in HFC heating is uniform, and heat losses from the surface are small.   At very much later times (curve *b*), the temperature distribution in HFC heating is more nonuniform than in induction heating.   Heat losses from the surface cause a marked drop. In practical applications, however, heating is carried out at so high a rate of power input, and therefore for so short a time, that the influence of the surface heat loss is small; hence the temperature differences in most cases are still acceptable.

II.   HIGH-FREQUENCY POWER SUPPLY

Usually the frequency of the alternating current as supplied is 60 cycles and in some cases 25 or 50 cycles.   For the majority of induction heating applications and for all HFC heating high-frequency current is being used.   For any given frequency the same power source can be used for any type of application.

A.   Selection of Power Supply

There are five types of high-frequency power supplies in use today. In the order of maximum obtainable frequency they are: transformers, mercury arc converters, motor generator sets, spark gap converters, and vacuum tube converters.   *Transformers* can be used only to a very limited extent: they transform the supply frequency in a given invariable ratio of 1:3, thus providing 180-cycle current from a 60-cycle supply line. Use of transformers for frequency transformation is extremely inefficient and therefore only rarely practiced.   *Mercury arc converters* are at present available for frequencies up to 1500 cycles and in sizes from 100 to 600 kw

output.   *Motor generator sets* have been built for frequencies up to 12,000 cycles; the largest unit in the United States is 1250 kw, whereas in Europe units as large as 2000 or 2500 kw have been made.   *Spark gap converters* are relatively limited in size, the largest units available being in the order of magnitude of 40 kw (input); frequencies up to 500,000 cycles (500 kilocycles) are available.   *Tube generators* are practically unlimited in frequency, reaching 100 or 200 megacycles (1 megacycle $= 10^6$ cycles). The largest individual tube has an output of approximately 500 kw, at 50 kilocycles.   The maximum output per tube decreases with increasing frequency and is perhaps 25 kw at 50 megacycles.[63]   Larger output can be obtained by connecting several tube circuits in parallel.

Generally speaking, mercury-arc converters and motor generator sets, and to some extent spark-gap generators and tube generators, are used for the same type of applications (except for frequencies beyond the range of spark-gap converters).   But between the two groups there is little overlapping.

B.   Motor Generators

In the United States motor generator sets are built in units up to 1250 kw, whereas in Europe units with 2000 to 2500 kw were in operation before the war.   Such sets for high frequencies include a motor and a generator, with an excitator mounted either coaxially or as a separate

PATH OF FLUX   FIELD COIL   AIR COOLING COILS

INNER-FRAME

NON-MAGNETIC   INNER FRAME

CORE COOLING PIPES

PATH OF AIR   ROTOR SLOTS

ROTOR

SHAFT
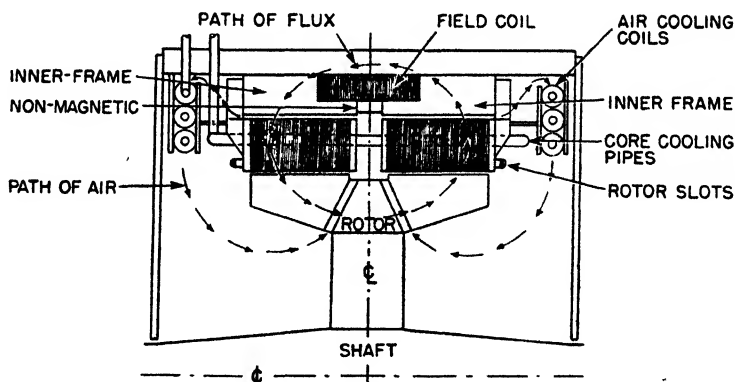
Fig. 191.   Rotating high-frequency generator.

unit.   For sets with an output below 250 kw asynchronous motors are employed, for larger units synchronous motors are the rule.   The motor, made for the supply frequency of 60, 25, or 50 cycles, is of customary design.   The high-frequency generator (Fig. 191) is of the inductor type,

[63] P. H. Brace, in *Induction Heating.*   American Society for Metals, Cleveland, 1946, p. 36.

in which the rotor does not carry a winding; the rotor is slotted and as the rotor slots pass before slots and teeth of the stator, the flux pulsates with a frequency determined by the speed of revolution and the number of teeth. The stator is excited by one coil which carries direct current. Small units rotate at 3600 rpm (with 50-cycle current 3000 rpm), whereas units above 250 kw are driven by synchronous motors and use 1800 rpm. The units are generally cooled; small units may be all enclosed in a water jacket, larger units are air-, water-, or sometimes hydrogen-cooled. Excitation current is provided either from a d-c generator mounted co-axially or from a unit as described in Volume I (page 163) for electrode control (Amplidyne, Rotatrol, Regulex). The latter type of machine, when applied, is used as an excitator and simultaneously for voltage regulation.

FIG. 192. Efficiency vs. load of motor generator set.

As with all machines efficiency is best at full load; in Figure 192 the loss of efficiency for part loads is shown.

C.   MERCURY-ARC CONVERTERS

The converter consists of three units: one low-frequency (60, 50, or 25 cycles) transformer, mercury-arc frequency converter tanks, and a high-frequency transformer.[64] Auxiliary equipment includes an a-c circuit breaker on the low-frequency side and electronic grid control for the converter tanks, and appropriate water cooling.

The two transformers may be built into one self-contained, oil-filled case. For large connected loads, above 500 kw, two separate cases are used. Similarly for small loads, below 500 kw, the six mercury-arc converters may be built with one single mercury pool, six graphite anodes, and six grids in one container. Figure 193 is a schematic wiring diagram for a mercury-arc converter. The primary of the low-frequency transformer is delta-connected, the secondary, zigzag; a reactor connects the neutral point of the transformer with the mercury cathodes of the arc rectifiers. The primary windings of the high-frequency transformer are center-tapped.

The mercury-arc frequency converter tanks have a steel casing, which a cooling coil protects on the inside against excessive temperature rise from the arc. A vacuum pump eliminates the air for operation of the arc *in vacuo*. The mercury is in contact with the casing, while the anode is carefully insulated from the casing and cooled by a large finned head. Output voltage and output power is controlled by a rheostat which changes the feedback conditions of the grid.

[64] S. R. Durand, *Electronic Ind.*, **4**, 74 (June, 1945).
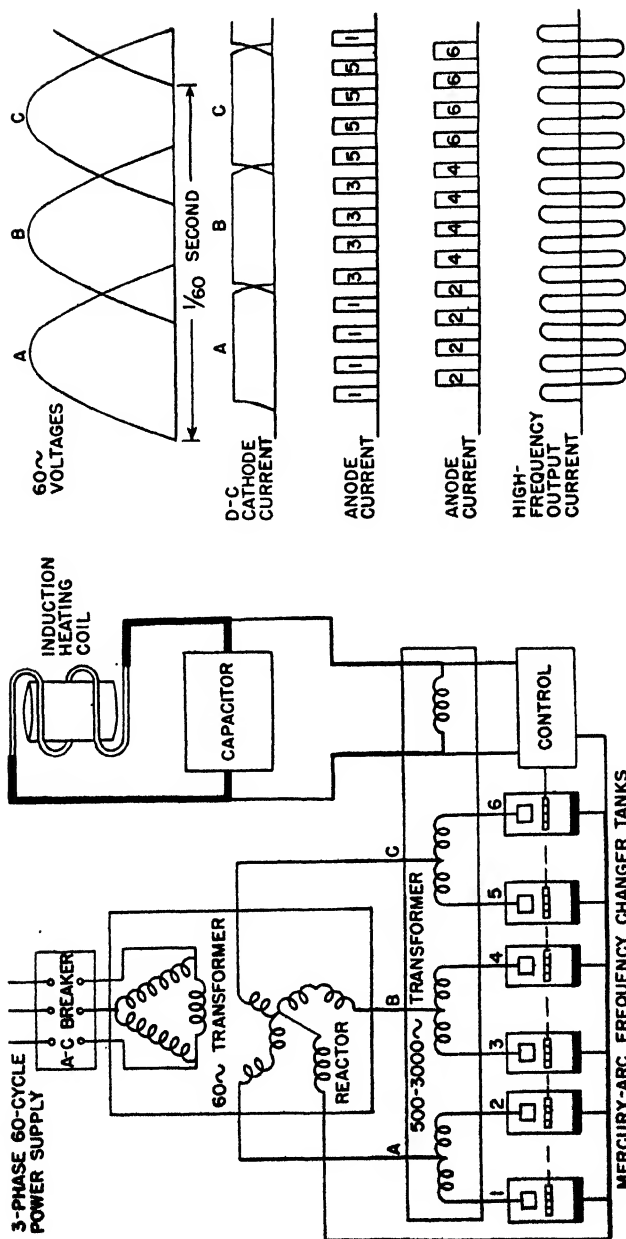
Fig. 193. Wiring diagram for mercury-arc converter.

Starting the converter from cold is effected in two steps by a starting electrode which is permanently located in the tank, but not always connected; and by changing the potential of the grid, the latter operation being controlled from the control cubicle.

These converters share with vacuum tube converters one important characteristic. The frequency is not fixed but changes with the electric characteristics of the load.

FIG. 194. Wiring diagram for spark-gap generators.

FIG. 195. Spark-gap electrodes. (Courtesy *Lepel High Frequency Laboratories, Inc.*)
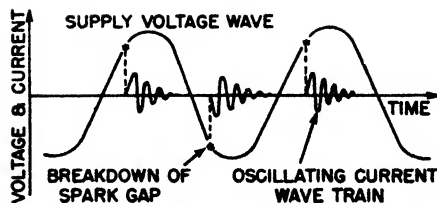
FIG. 196. Damped oscillations in spark gaps.

D. SPARK-GAP GENERATORS

Spark-gap generators do not operate at any one given frequency, even if the load circuit remains unchanged. Instead, a damped oscillation is excited by the spark at regular intervals (Fig. 194). The "60-cycle generator" must be of high voltage (between 2000 and 6000 v) and may consist of a high-voltage transformer. The electrodes for low-power generators [65] may consist of carbon *vs.* mercury, the system operating in hydrogen. For higher power, tungsten is used in multigap air- or water-

[65] P. H. Brace, in *Induction Heating.* American Society for Metals, Cleveland, 1946, p. 36.

cooled arrangements (Fig. 195). Generated frequencies vary with design and may be between 15,000 and 300,000 cycles. An example of the damped oscillation obtained with spark-gap generators is shown in Figure 196.

E. Tube Generators

Tube generators [66] for heating purposes consist of three main parts: a power transformer, a rectifier, and an oscillator. The frequency of the heating circuit is governed by its load characteristics. To function properly the load circuit must be resonant and is fed from a full wave rectifier and is controlled by a grid-controlled vacuum tube. The rectifier operates on the a-c side at high voltage, approximately 7500 to 15,000 v, provided by the transformer. Supply can be three-phase or single-phase, each phase of course requiring at least two rectifier tubes; thus the three-phase rectifier necessitates six tubes.
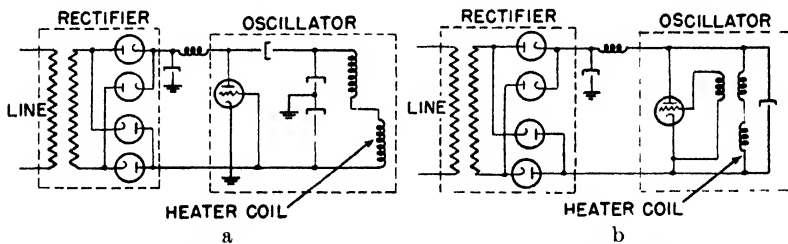
Fig. 197. Basic circuits for high-frequency tube generators.[66]

The basic circuits are shown in Figure 197. Four to six rectifier tubes are usually provided; of the two grid-controlled tubes only one is shown in the basic diagram. Heat generation in the tubes, being appreciable, the latter require cooling, customarily by water or a blower. Because of the heat storage in the tubes, the cooling must continue for some time after switching off the tubes, and automatic time-delay locks can insure continued cooling after disconnecting the power.

The frequency is maintained by exciting the grid from the resonant load circuit. In the Colpitt's circuit (Fig. 197a) the grid-to-cathode control voltage is obtained by center-tapping the resonance condenser; in the coupled grid circuit (Fig. 197b) the control voltage comes from a coil coupled inductively with the resonance inductance. In the so-called Hartley circuit the inductance is center-tapped rather than the condenser (as in the Colpitt's circuit).

If low voltages and high currents are required for heating, the part marked "heater coil" may serve as primary for an air transformer, the

[66] See, for example: J. P. Jordan, *Trans. Am. Inst. Elec. Engrs.*, **61**, 831 (1942); W. M. Roberds, *Electronic Ind.*, **4**, 108 (1945).

secondary of which may have but one or two turns and surrounds the work piece.

For more detailed description of tube generators, reference is made to special literature.[67]

Tube generators are completely enclosed, the exterior appearing merely as a steel cabinet with some built-in instruments.   By opening various doors the different parts should be easily accessible (Fig. 198);

FIG. 198.   View of tube oscillator cabinet.
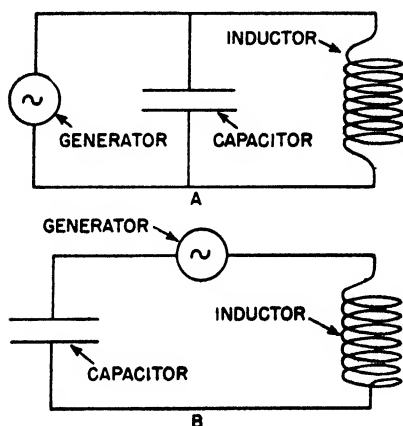
FIG. 199.   Resonance circuits: A, parallel resonant circuit; B, series resonant circuit.

space requirements change greatly with frequency.   A normal output per square foot at frequencies of 100–1000 kc is 2–4 kw, whereas at several hundred megacycles only 0.4–0.6 kw per sq ft is obtained.

F.   Resonance Circuits

The output of any of the above power sources is limited by the current which the weakest element of the source can carry.   It is therefore generally desirable to operate the circuits in resonance, that is, the condition in which inductive and capacitive load balance each other completely, leaving a pure ohmic load.   Resonance may be obtained in parallel or in series circuits, as shown in Figure 199.   Each circuit is resonant at only one given frequency, which may be determined from:

$$f = 1/(2\pi \sqrt{LC}) \qquad (34)$$

[67] *Applied Electronics*, compiled by staff of Massachusetts Institute of Technology, Wiley, New York, 1947.   W. Bendz, *Electronics in Industry*, Wiley, New York, 1947. E. V. Eastman, *Fundamentals of Vacuum Tubes*, McGraw-Hill, New York, 1941.

where L = inductance of the entire circuit in henries, C = capacitance of the entire circuit in farads, f = frequency in cycles per second. Deviation from this frequency causes a drop of the obtainable current, a drop which is more marked for smaller resistances (Fig. 200).
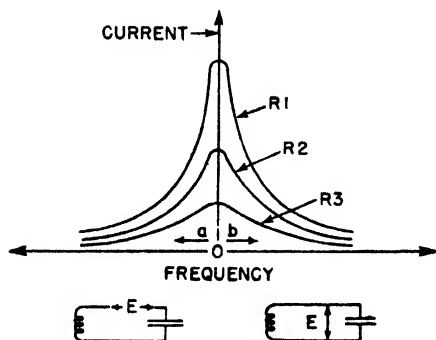
Fig. 200. Current *vs.* deviation of frequency from resonance value.

O, resonance frequency:
   a, frequencies below ⎫
   b, frequencies above ⎭ resonance.

Constant voltage E. Influence of frequency on current is more marked with small resistance (R_1) than with large one (R_3).

III. INDUCTION FURNACES AND APPLIANCES

A. ELECTRICAL PROBLEMS

1. Depth of Penetration

In induction heating, heat is not generated uniformly over the entire cross section. Because of the skin effect (Vol. I, page 58), a great part of the total heat is generated near the surface. This concentration becomes more marked at higher frequencies, and at radio frequencies heat generation may be assumed to take place entirely at the surface. The degree to which "heat generation at the surface" may be assumed, instead of the actual generation over a finite thickness, depends not only on the frequency and the actual energy distribution, but also on the duration of the heating process. For very short processes, in which only a surface effect is attempted (page 264), the actual distribution is more important than in through heating processes, as in annealing or melting.

The skin effect can be characterized by the "depth of penetration":

$$p_p = 3560\sqrt{\rho/\mu f} \tag{35}$$

where p_p = depth of penetration (cm), ρ = electric resistivity (ohm $\times$ cm), f = frequency, and μ = permeability. The expression "depth of penetration" is used in literature for two different magnitudes, and frequently sufficient explanation is lacking. The two expressions differ by a factor of $\sqrt{2}$, one being defined by Equation (35), the other by:

$$p_p' = 5030\sqrt{\rho/\mu f} \tag{35a}$$

The relationship of Equations (35) and (35a) may be understood from

Figure 201, representing schematically the current distribution near the surface plotted against the distance from the surface. If the value of current at the surface is I_s, then p_p is the thickness at which the current has dropped to $(I_s)^{1/e}$. If the area under the current distribution curve is A, then p'_p is defined by

$$p'_p = A/(I_s)^{1/e} \qquad (35b)$$

The value of p_p can be easily read[68] from the graph in Figure 202. Equation (35) holds rigidly only if the thickness or diameter of the piece to be heated is large as compared with the value of p'_p.

The actual distribution of current density is illustrated by Figure 203, which holds for a copper cylinder—$\rho = 1/(50 \times 10^4)$ ohm $\times$ cm,
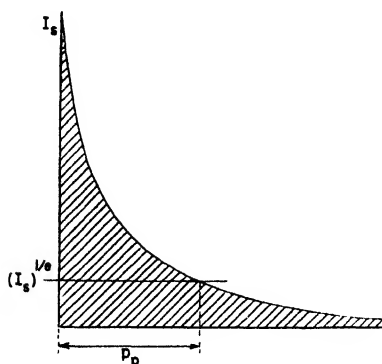
FIG. 201.   Meaning of depth of penetration.
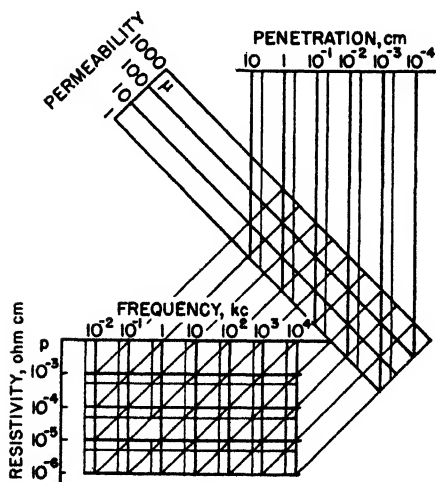
FIG. 202.   Chart for determining depth of penetration.
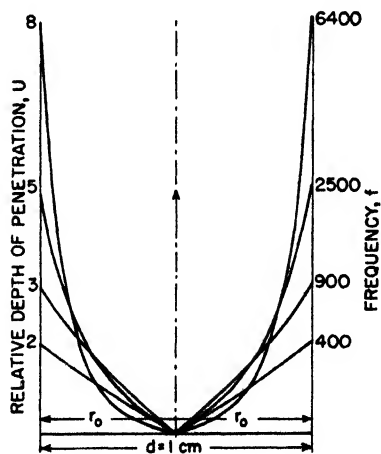
FIG. 203.   Current distribution in copper cylinder: f frequency; U (see Eq. 38); r radius (Fischer).

diameter, d, $= 1$ cm—and shows the current distribution over the cross section of the cylinder.

[68] H. F. Storm, *Trans. Am. Inst. Elec. Engrs.*, **63**, 749 (1944).

The resistance, R, of a section (l cm long) of a cylinder of great length, placed coaxially in a coil and exposed to induction heating is:

$$R = \pi d\rho/lp_p \tag{36}$$

Obviously the resistance is a function of the depth of penetration.

The heat generation is proportional to the square of the current density and therefore drops even more rapidly than the latter with increasing distance from the surface. In Figure 204, the heat generation (w per cu cm) in per cent of the surface value is plotted against multiples of the depth of penetration. From the surface to a value p_p the heat generation per unit volume has dropped from 100 to 24%. The total heat generation may be ob-

FIG. 204.   Energy distribution in induction heating.

tained from the integral of the curve.   Within a layer of the thickness, p_p, approximately 94% of the entire heat is generated.[69]

Equation (36) and Figures 203 and 204 are accurate if the diameter of the piece is large as compared with the depth of penetration.   If the diameter of the cylinder is at least four times as large as the depth of penetration, the results are accurate to within 1%; for cylinders of smaller diameter the errors increase rapidly and reach 5% if the diameter is only 3.5 times the depth of penetration.   This approximation (Eq. 36) is usually sufficient.   Otherwise a series development is required.[70]

2. Power Generation—No End Effects

The power generated in the load can be calculated, based on the concept of induction heating as a coreless transformer.   A complete and rigid calculation has been published by Wever and Fischer.[71]   The development of equations for load, resistance of the coil, etc. leads to Bessel's functions and will not be repeated here.   The authors arrive at the following formula for the power generated in a long cylindrical load, with constant electric and magnetic properties:

$$W_1 = I^2 N_E f \mu r^2 P_1 \times 8\pi^3 \times 10^{-9} \tag{37}$$

[69] F. T. Chesnut, *Westinghouse Eng.*, **1**, 76 (1941).

[70] M. B. Dwight and M. M. Bagai, *Elec. Eng.*, **54**, 312 (1935); **55**, 187 (1936).

[71] F. Wever and W. Fischer, *Mitt. Kaiser-Wilhelm Inst. Eisenforsch. Düsseldorf*, **8**, 149 (1926).

where W_1 = power (w/cm), I = current (amp), N_E = number of turns (per cm coil length), f = frequency (cycles/sec), μ = permeability of charge, r = radius of charge (cm), and P_1 = a special function. Values of P_1 have been calculated as a function of U, which may be described as relative depth of penetration, and are shown in Table XVI.

TABLE XVI

VALUES OF P_1 AND P_2

U	P_1	P_2	U	P_1	P_2
0	0	1	4.5	0.2642	0.3159
0.5	0.0313	0.9991	5	0.2416	0.2841
1	0.1225	0.9846	5.5	0.2229	0.2582
1.5	0.2459	0.9083	6	0.2070	0.2368
2	0.3437	0.7726	8	0.1608	0.1769
2.5	0.3778	0.6218	10	0.1311	0.1448
3	0.3600	0.4990	15	0.0896	0.0940
3.5	0.3256	0.4145	20	0 0682	0.0707
4	0.2921	0.3570			

$$U = r'p_p \tag{38}$$

In Equation (37) the resistance of the charge does not appear directly, but is hidden there because P_1 is a function of p_p and thereby of the resistivity. The function, P_1, has a marked maximum. The two branches below and above the maximum can be conveniently replaced by approximations. For $U < 1$:

$$P_1 = U^2/8 \tag{39}$$

and for $U > 3$:

$$P_1 = (\sqrt{2}/U) - (1/U^2) \tag{40}$$

For $U > 15$, it is permissible to neglect $1/U^2$ against $\sqrt{2}/U$; Equation (37) may then be replaced by the approximate Equation (41):

$$W_1 = 4\pi^2(IN_E)^2 r\sqrt{\mu f \rho 10^9} \times 10^{-9} \tag{41}$$

This formula, first derived by Ribaud,[72a] has recently been developed by Storm,[72b] using concepts commonly applied to a-c engineering.

3. Reactance Power

It is possible to calculate the reactance power of the load (expressed in volt-ampere) in a manner similar to that for wattage. By using the same notations as before, and with W_L as reactance power of the second-

[72a] M. G. Ribaud, *J. phys. radium*, **4**, 185, 214, 251 (1923); **6**, 295 (1925).
[72b] H. F. Storm, *Trans. Am. Inst. Elec. Engrs.*, **63**, 749 (1944), Equation (38).

ary referred to the primary (in va per cm) and P_2 as a special function, the reactance power can be derived from:

$$W_L = I^2 N_E^2 f r^2 \times 8\pi^3 \times 10^{-9} \times (1 - \mu P_2) \tag{42}$$

The function P_2 has been calculated and is represented in Table XVI. The nature of P_2 is quite different from that of P_1. The value of P_2 decreases steadily from 1 (for $U = 0$) to 0 for $U = \infty$. However, the characteristic value of $U = 2.5$ is a turning point, and it again becomes possible to obtain approximate expressions representing the function of P_2. For $U < 1$:

$$P_2 = 1 \tag{43}$$

and for $U > 5$:

$$P_2 = \sqrt{2}/U \tag{44}$$

4. Selection of Frequency

Selection of frequency must be considered from two angles: heat generation and electric effects. The heat generation depends upon depth of penetration. The higher the frequency, the smaller the depth of penetration and the more localized the heating. This has particular significance for heating for selective hardening and is discussed later (page 264).

Much has been said about the existence of an optimum frequency; it can be proved that at values of $U > 15$ the electric efficiency does not change with frequency, and at values of $U < 1$, which occur but rarely in practice, the electric efficiency increases with frequency indefinitely without reaching a maximum. For values of U between these two limits conditions have not yet been investigated. The rate of energy input, however, increases with frequency at all values of U (Eqs. 39 and 40), and, inasmuch as the rate of heat losses is for a given design independent of frequency, the total efficiency does change with frequency, as shown below. An analysis is possible based on Equations (39) and (40). By introducing successively the values of U and p_p, these equations can be transformed as follows. For $U < 1$:

$$W_1 = (IN_E)^2 8\pi^5 r^4 \frac{f^2 \mu^2}{\rho} \times 10^{-18} \tag{37a}$$

and for $U > 3$:

$$W_1 = (IN_E)^2 \pi \left(\frac{r\sqrt{2}}{3560} \sqrt{\rho\mu f} - \rho \right) \tag{37b}$$

The first expression in parentheses $(r\sqrt{2\rho\mu f}/3560)$ equals $\sqrt{2}U\rho$; the entire expression in parentheses $(r\sqrt{2\rho\mu f}/3560 - \rho)$ is $(U\sqrt{2}\rho - \rho) = \rho(U\sqrt{2} - 1)$.

If U is sufficiently large, $l'\sqrt{2} - 1 \approx U$, and the expression may further be simplified:

$$W_1 = (IN_E)^2 \pi \frac{r\sqrt{2}}{3560} \sqrt{\rho\mu f} = (IN_E)^2 \frac{r}{804} \sqrt{\rho\mu f} \qquad (37c)$$

This formula, incidentally, is the same expression, Equation (41), as given by Storm,[72b] which holds with not more than 1% error if $U > 100$.
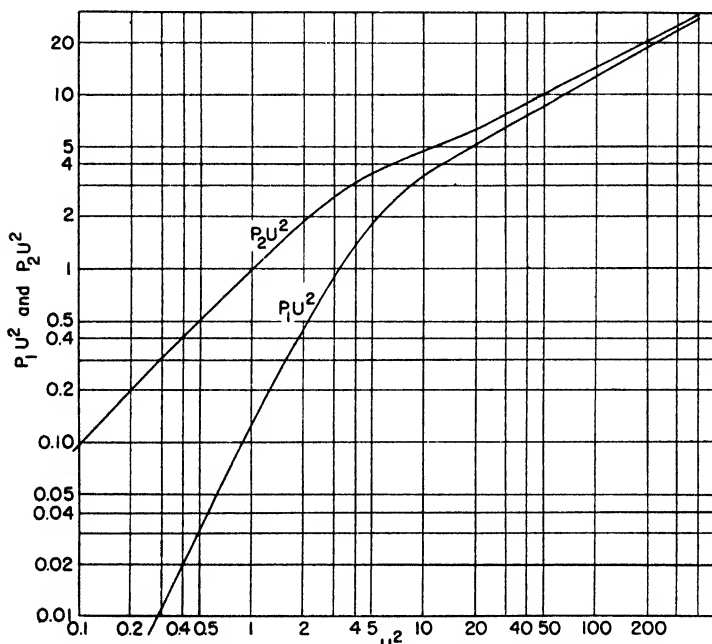
FIG. 205.   Power and reactance power in load as function of U^2.

In Equations (37a), (37b), and (37c), the power, W_1, increases with frequency; however, the rate of increase is very much higher for $U < 1$ than for $U > 3$.   For $U < 1$ the power increases with the square of the frequency but for $U > 15$ only with the square root of the frequency.   It is desirable to work with frequencies large enough to make $U \geqq 2.5$; beyond that the gain in power by increased frequency is limited.   In Figure 205 two curves are plotted: values of P_1U^2 and P_2U^2 are ordinates and U^2 are abscissas.   The values of U^2 are proportional to the frequency.   The increase of power with increasing frequency is initially very rapid but slows down considerably.   The reactance power increases initially at a still more rapid rate; at high values of U^2, however, the two almost coincide.

It is not possible to write in Figure 205 the abscissa values directly in cycles per second because P_1 and P_2 are functions of U. For each material and for each diameter, a different part of the abscissa axis is involved; the flattening out occurs at different frequencies.

Brown [73] points out the following relationships between frequency and various design items: (a) the reactance at the input terminals of the work coil varies directly with frequency, (b) the resistance at the terminals of the work coil varies with the square root of the frequency; (c) the current in the work coil, for a constant power input, varies inversely as the one-fourth power of the frequency; (d) the voltage in the work coil, for a constant power input, varies directly as the three-fourth power of the frequency.

Although no frequency optimum for power generation or electric efficiency exists, it may be necessary in heating to select a given frequency to obtain the desired skin effect for surface heating (see page 264).

From Equations (37) and (42) it can be deduced that the reactance power for any one given value of useful power increases approximately with the square root of the frequency. The size of a condenser for a given desired reactance power changes in direct proportion to the frequency. Therefore the size of the condensers necessary to compensate for the inductance of the coil and to produce a power factor of one, decreases in proportion to the square root of the frequency.

5. Inductor Efficiency

(a) Electric Efficiency

The same concentration of the current at the surface occurs within the coil as in the charge. Only a very thin layer of the copper coil carries the current. The balance of the cross section acts almost only as "cooling fin" for the current-carrying layer. To permit loading the coil with a heavier current, water-cooled hollow coils are usually used.

The depth of penetration in copper having an electric resistivity of 2.04×10^{-6} ohm $\times$ cm at 70 F, is found from the following table:

f (cycles/sec)	10^2	10^3	10^4	10^5	10^6
p_p (cm)	0.718	0.225	0.0718	0.0225	0.00718

The resistance of the copper coil can be approximated by:

$$R_1 = 1.8\, N_E^2 \sqrt{f} r_1 j_R \times 10^{-6} \tag{45}$$

where R_1 = resistance of inductor coil per unit length (ohm/cm), r_1 = inside radius of inductor coil, and j_R = correction factor. The latter is defined by:

$$j_R = H/(H - H_i) \tag{46}$$

[73] G. H. Brown, *Electronics*, **17**, 124 (1944).

where H is the length of the coil and H_i is the sum of all spaces between turns. For resistances of the inductor coil other than 2.04×10^{-6} ohm-cm, multiply the resistance in Equation (45) by:

$$702 \sqrt{\text{resistivity (ohm} \times \text{cm)}}$$

Losses in the primary coil per cm length, W_P, can be found from:

$$W_P = I^2 R_1 \qquad (47)$$

The electric inductor efficiency η_E, can be expressed by the ratio:

$$\eta_E = W_1/(W_1 + W_P) \qquad (48)$$

To analyze the conditions for high efficiency, the approximate equations (37a to 37c) rather than the exact equation (37) should be used, because the latter contains the function P_1, which is mathematically complex. Hence, for $U < 1$:

$$\eta_E = \frac{1.36 \, r^4 f^2 \mu^2}{1.36 \, r^4 f^2 \mu^2 + \rho \cdot j_R r_1 \sqrt{f} \times 10^{10}} \qquad (49)$$

The case of $U < 1$ applies mostly to heating appliances for thin material, but almost never occurs in melting. It would occur, for instance, when heating a brass wire, 0.02 cm thick ($r = 0.01$ cm) at a frequency of 10^6 cycles/sec; the resistivity is $1/(7 \times 10^4)$ ohm $\times$ cm; $\mu = 1$. Then, $U = 0.74$ and, with an inside diameter of the inductor coil of $r_1 = 0.5$ cm and with $j_R = 1$, the electric efficiency would be:

$$\eta_E = \frac{0.01^4 \times 10^{12} \times 1.36}{0.01^4 \times 10^{12} \times 1.36 + \dfrac{1}{7 \times 10^4} \times 0.5 \times 10^3 \times 10^{10}} \sim 0.0002$$

Obviously it would be impossible to get heat into the wire unless the frequency is raised to approximately 10^{10}. With this frequency, however, $U = 7.4 \times 10^5$ and Equation (49) no longer applies. At this value of U the electric efficiency would be independent of frequency, roughly 5% (see Eq. 50). Obviously, it is extremely difficult to heat thin good conductors by induction.

The case is different for $U > 15$, when the approximate expression is:

$$\eta_E = \frac{\dfrac{r}{j_R r_1} \sqrt{\dfrac{\mu \rho}{\rho_c}}}{\dfrac{r}{j_R r_1} \sqrt{\dfrac{\mu \rho}{\rho_c}} + 1} \qquad (50)$$

where ρ_c denotes resistivity of the coil.

The maximum efficiency would be secured if $r/r_1 = 1$, which for practical reasons is not obtainable. The upper limit of efficiency, with

$r/r_1 = 1$ and $j_R = 1$ is:

$$\eta_{E\,\text{max}} = \frac{1}{1 + \sqrt{\rho_c/\rho\mu}} \tag{50a}$$

This equation is represented in Figure 206. The importance of placing the inductor coil as close as possible to the surface of the charge is different for different materials.

In Figure 207 the efficiency, η_E, is plotted against the ratio of the radii for different values of $\sqrt{\mu\rho/\rho_c j_R}$.
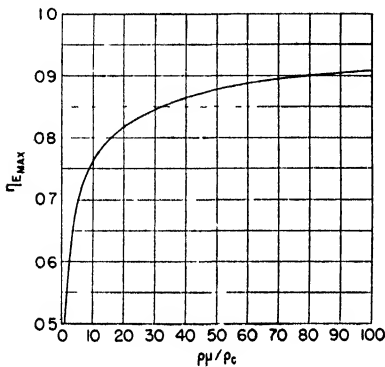
FIG. 206. Maximum electric efficiencies for load filling coil entirely ($r/r_1 = 1$).
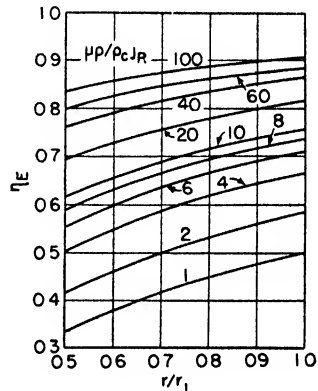
FIG. 207. Electric efficiencies for various values of r/r_1.

(b) Thermal and Over-all Efficiency

The coil is always kept at room temperature; since heat loss occurs from the surface of the load to the surrounding, heat insulation is frequently placed between the load and the coil. Such insulation is necessary for melting furnaces (the lining forming a thermal insulation), but is omitted when heating for extremely short cycles. The thicker the insulation, the smaller the heat losses, but, as shown in Equation (50), the higher the electric losses. There will be an optimum value for r/r_1, resulting in smallest over-all losses.

The heat losses can be approximately expressed by Equation 51 (in watts):

$$W_H = k\,\frac{r_1 + r}{2(r_1 - r)}\,2\pi\,\frac{t_s - t_1}{3.413} \tag{51}$$

W_H = rate of heat losses from the load (w/ft length), k = thermal conductivity (Btu/ft, hr, F), t_s = surface temperature (F) of charge, and t_1 = surface temperature (F) of coil. This equation does not include the

boundary resistance between charge and insulation or between insulation and coil; it is based on the assumption that the entire space between charge and coil is filled by insulation.

The energy which is being lost from the surface of the charge by heat conduction, or radiation, must first be transferred to the charge. This transfer cannot be made without additional electric losses. Conditions are similar to those in arc furnaces, where heat losses from the furnace shell have to be supplied through the electrodes and busses, causing additional electric losses (Vol. I, page 200). It is not possible, therefore, to write an expression for the thermal efficiency and, furthermore, Equation (51) is meaningless without reference to additional electric losses.

The following relationships are self-evident:

(1)   Useful Heat = Heat in Load − Heat Losses

(2)   Total Efficiency = Useful Heat/Total Energy Input

(3) Total Energy Input = Useful Heat + Heat Losses + Electric Losses in Coil

Therefore:

$$\text{Total Efficiency} = \frac{\text{Heat in Load} - \text{Heat Losses}}{\text{Heat in Load} + \text{Electric Losses in Coil}}$$

By introducing the values from Equations (37c and (51) and calling the total efficiency η_t, the above expression may be written for $U > 15$ as:

$$\eta_t = \frac{(IN_E)^2 \dfrac{r}{804} \sqrt{\rho\mu f} - k\,\dfrac{\Delta t}{3.413}\dfrac{r_1 + r}{r_1 - r}\dfrac{1}{30.8}}{(IN_E)^2 \dfrac{r}{804}\sqrt{\rho\mu f} + (IN_E)^2 \dfrac{j_R r_1}{804}\sqrt{\rho_c f}} \qquad (52)$$

Since heat losses refer to a length of 1 ft, and electric losses refer to a length of 1 cm, a conversion factor of 30.8 appears in the equation. For simplification:

$$\frac{804\, k\Delta t}{30.8 \times 3.413\,(IN_E)^2\sqrt{\rho_c f}\, j_R r_1} = J$$

where $J\,\dfrac{r_1 + r}{r_1 - r}$ is the ratio of heat losses to electric coil losses. Since:

$$\frac{r}{j_R r_1}\sqrt{\frac{\mu\rho}{\rho_c}} = \frac{\eta_E}{1 - \eta_E}$$

it is possible to write Equation (52) as follows:

$$\eta_t = \eta_E - J(1 - \eta_E)\,\frac{1 + \dfrac{r_1}{r}}{\left(\dfrac{r_1}{r} - 1\right)} \qquad (52a)$$

It should be remembered that the expression for η_t is not independent of frequency, because the factor J increases with the square root of frequency. As stated before, the power input grows with frequency, and therefore the over-all efficiency also changes with frequency.

TABLE XVII

RATIO OF RADII AND LOSS FUNCTION

$\dfrac{r}{r_1}$	$\dfrac{(r_1/r) + 1}{(r_1/r) - 1}$	$\dfrac{r}{r_1}$	$\dfrac{(r_1/r) + 1}{(r_1/r) - 1}$
0.5	3.0	0 8	9 0
0.6	4.0	0.9	19 1
0 7	5 65	0.95	37.9

The total efficiency is smaller than η_E by an amount which is a function of r/r_1. The expression $\dfrac{1 + (r_1/r)}{(r_1/r) - 1}$ increases rapidly as $r\ r_1$ rises from 0.5 to 1, as may be seen from Table XVII. Low r/r_1 ratios mean good insulation—and high ratios, poor insulation. However, the electric efficiency increases with increasing values of r/r_1. Hence there is an optimum value of r/r_1 for every value of r_1 or, by proper substitution, for every value of r. The general equation for the ratio r/r_1 is too complicated for practical purposes, even if based on Equation (52a). For values of $U < 15$ the equations equivalent to (52a) become even longer, and the general solution is unwieldy. Individual investigations by point-to-point plotting are, however, feasible.

It is incorrect to plot heat losses and electric losses independently against the ratio of the radii (charge and coil), add the two curves, and thus determine the ratio

FIG. 208. Optimum wall thickness in induction heating—continuous operation: a, rate of total energy generation in the charge (kw), b, electric efficiency; c, rate of power input in the coil.

yielding smallest losses. The fact that the total heat to be generated in the load depends on the heat losses makes this approach impossible.

Relationships may be better understood from Figure 208. The ratios of the radii are plotted as abscissas. Three curves are shown.

Curve a has as ordinates the total energy to be generated in the charge; this energy is composed of the useful heat plus the heat losses. The latter increase with increasing ratio, r/r_1. Curve b represents the electric efficiency, which also increases with increasing ratio of the radii. Curve c represents the power input in the coil. It is found by dividing the total heat in the load by the electric efficiency. This third curve shows a minimum representing the most economical ratio of radii.

6. Finite Length of Heater

All equations to this point refer to a 1-cm long section of a very long body heated in a very long coil; in other words, end effects have been neglected. Esmarch [74] has developed graphs and equations which permit consideration of the finite length of coil and body. To use his method the power, W_1, must be referred to the full length of the unit rather than to 1 cm. Equation (41) is to be replaced by Equation (53), for which the following notations apply: W_t = total power in watt for body l cm long; l_1 = length of coil; l_2 = length of heated body; and J_1 and J_2 = correction factors.

$$W_t = (IN_E)^2 \frac{r}{8200} \sqrt{\rho\mu f}\, J_1 J_2 l_2 \tag{53}$$

J_1 and J_2 are plotted in Figures 209 and 210. The same correction factors apply to the reactive power (Eq. 42).
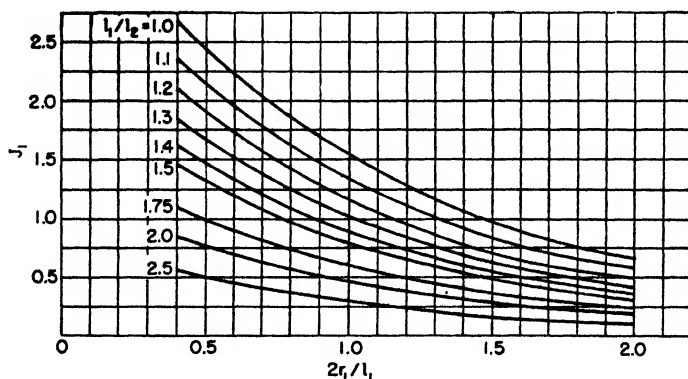
Fig. 209.   Influence of coil length on power transmission.

7. Coil Voltage.   Power Factor

The voltage to be impressed on the inductor coil is determined by the number of turns, a number which is contained in the expressions for power and reactance power. The expressions for power and reactance power

[74] W. Esmarch, *Wiss. Veröffentl. Siemens-Konzern*, **10**, 172 (1931).

of the load (both referred to the primary coil), and for the losses in the coil have been given above. The reactance power of the coil itself (in henry per cm axial length of coil) may be calculated from its inductance, L_C:

$$L_C = 4\pi^2 r^2 N_E \times 10^{-9} \tag{54}$$
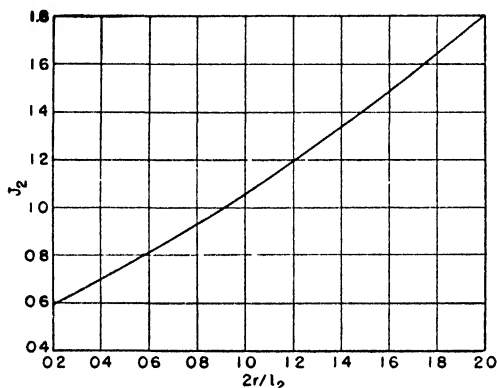
Fig. 210.   Factors J_2.

The reactance power of the coil, W_{LC}, per unit length is:

$$W_{LC} = I^2 2\pi f L_C \tag{55}$$

The total reactance power W_{Lt} is the difference:

$$W_{Lt} = W_{IC} - W_L \tag{56}$$

where W_L is found from Equation (42). The voltage of the furnace is found from the impedance (in v per cm axial length):

$$E = \frac{\sqrt{W_{Lt}^2 + (W_1 + W_P)^2}}{I} \tag{57}$$

It is also possible to determine the power factor at the terminals. Since it is very low, compensation by a capacitance load is always necessary:

$$\cos \varphi = \frac{W_1 + W_P}{\sqrt{W_{Lt}^2 + (W_1 + W_P)^2}} \tag{58}$$

B.   MELTING FURNACES

1. Core Type Melting Furnaces

(a) Applications

The main application is for the melting of brass. Other nonferrous metals are also melted, particularly aluminum, zinc, and nickel-silver

(zinc for production of ingots for rolling).   Melting bronze and copper is
made difficult by the short life of the lining obtained with these metals.
Steel and ferrous metals are sometimes melted in core type induction
furnaces, but with a few exceptions this field is taken over by coreless
induction furnaces and by arc furnaces.   One such exception is the du-
plexing of cast iron, molten in a cupola and brought to the desired melting
temperature in a core type induction furnace.

(b) *Principle and Types*

The principle of core type melting furnaces is simply that of a trans-
former; the secondary coil consists of one turn only, this turn being the
metal which is to be melted.   The voltage in the channel is necessarily
very low (it equals the voltage in the inductor coil divided by the number
of primary turns), and therefore the current is high.   Currents of many
thousand amperes are the rule.   Designs using two or three "turns" of the
secondary have been attempted, but mechanical difficulties have pre-
vented success, and practically all core type melting furnaces have only
one secondary turn.   Each core type melting furnace consists of three
main parts: a refractory container, providing for a closed loop of metal,
an inductor coil as primary, and a laminated transformer core providing
for a close magnetic coupling between the two.   In addition a casing and
means for charge and discharge must be provided.
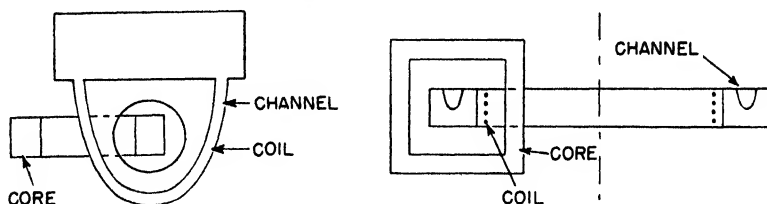
Fig. 211.   Core type induction furnaces with (left) vertical and (right) horizontal channel.

Two main types exist: furnaces with vertical channels and furnaces
with horizontal channels (see Fig. 211).   The high current in the molten
metal causes high electromagnetic forces.   Adjacent particles of the
metal, through which parallel paths of current flow, attract each other
strongly.   In furnaces with horizontal channels—the older design—this
mutual attraction results in what is known as the "pinch effect."   The
forces in the metal tend to cause local contraction, which may result in
interruption of the current.   As soon as the current path is interrupted,
the forces stop and the metal may flow together again.   However if the
cooling surface is large enough, the metal freezes before reuniting and the
melting process is interrupted.   Even if this does not happen the metal
spatters, making current absorption irregular.   The pinch effect increases

with power consumption and with frequency and therefore the connected load must be limited in such furnaces. Also, such furnaces are preferably operated at frequencies of 25 cycles and below. For these reasons furnaces with horizontal channels are practically abandoned today and will not be discussed further.

The pinch effect has been studied in detail by Hering.[75] The difficulties arising from the electromagnetic stirring have been turned into an advantage in the vertical channel furnaces, to which all of the following discussion refers.

(c) Design

A vertical channel furnace is shown in Figure 212. The secondary channel is formed either in rammed-in cement, or in a preformed refrac-
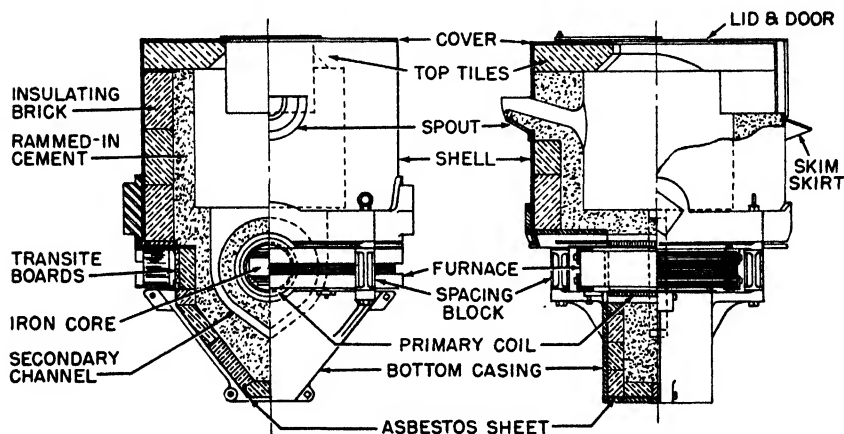
FIG. 212. Core type induction furnace with vertical channel.
(Courtesy *Ajax Electric Furnace Co.*)

tory brick. The loop of the secondary is formed by the V-shaped channel and is closed by the "crucible." The coil is arranged within the loop and parallel to it and, in view of the high temperatures, is insulated with asbestos or with fiber glass. The outside of the container of the channel is insulated, and the insulation is contained in a casing. Charging is done through the top, and discharging through a spout by tilting the furnace.

CHANNEL

Form and dimensions of the channel are of main importance. The dimensions of the channel govern the output of the furnace and are subject

[75] C. Hering, *Trans. Electrochem. Soc.*, 11, 329 (1907); 15, 257 (1909). E. F. Northrup, *Phys. Rev.*, 24, 6 (1907).

to the following considerations.   The cross section of the channels is in the order of magnitude of 3 sq in., the size being determined by resistance requirements and by the necessity for cleaning.   The current density in the channel may reach values of 5000 amp per sq in.   The height or length of the channel determines the space available for core and coil. With a given current in the channel the power is governed by the voltage between the ends of the channel; this voltage is proportional to the number of turns of the coil, and the cross section of the core depends on the required magnetic flux.   The larger the opening, the more turns can be provided and the higher the connected load.   Various shapes of the channel are in use (Fig. 213), the cross section usually being rectangular.
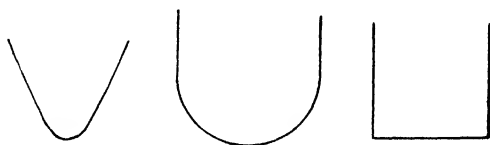
FIG. 213.   Shapes of channels.

Selection of the material of the lining depends on the metal to be melted.   Clay is used for yellow brass, whereas mullite, a mixture of magnesia and alumina, or corundum (a material high in alumina content) is used for red brass and bronze.   For aluminum melting furnaces, silica is being used.

The channel refractory can either be made of special brick or can be rammed into place and fired by the melting metal.   In the latter case a wooden form, which is burned for drying the lining, or a metallic form to be withdrawn after drying the lining, is used; a nickel–silver resistor ribbon is placed in the form and current, passing through the ribbon heater, heats it and ignites the wood.

As oxides and dirt from the charge, or corrosion products from the interaction between charge and lining, deposit in the channel, the cross section of the latter and therewith the effective resistance change.   For this reason, and because of the danger of clogging, the channel must be cleaned periodically.   This is done by pulling chains through the V- or U-shaped channels of brass or bronze melting furnaces.   In aluminum melting furnaces, with a rectangularly shaped channel (Fig. 214),[76] cleaning is done through openings in the horizontal bottom part of the channel. These openings are closed in operation by ceramic plugs, and therefore cleaning requires emptying of the furnace.   To allow longer intervals between shutdowns for cleaning—three to four weeks and longer—a dirt-collecting chamber is provided below the bottom channel.

[76] M. Tama, *Metal Progress*, **44**, 967 (1943); *Mech. Eng.*, **66**, 731 (1944).

Figure 214 represents a furnace with two channels, which are provided in parallel sometimes for increasing the output and sometimes to represent two or three secondaries of a three-phase transformer. The container on top of the channel stores solid metal before melting, as well as molten metal before pouring. The container capacity, expressed in volume or weight of the metal, is determined by the size of the largest casting or ingot to be poured from the furnace and by the necessity of
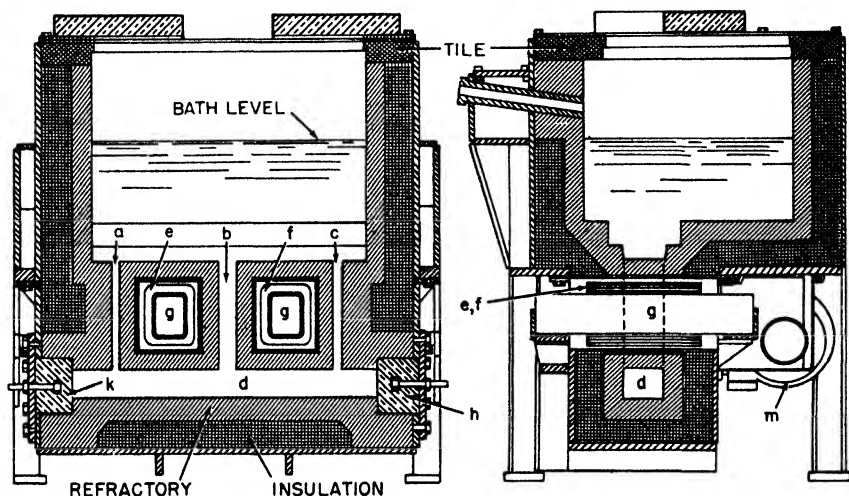
FIG. 214. Aluminum melting furnace: a, b, c, channels for molten metal; d, chamber for collecting dirt and dross; e, f, transformer winding; g, transformer core; h, k, ceramic plugs; m, blowers for cooling of coil.[76]

storing molten metal between castings. A further consideration is the size of scrap; the container must obviously be able to absorb the largest pieces. Finally should alloying or slagging of the metal be necessary, a container is required for storing the metal in quiescent state, because in the channel the metal is in rapid movement.

After the volume of the container is selected, the shape is chosen. The greater the height, the higher the pressure that is exerted on the metal in the channel, and the less the movement. If the height is not great enough, the bath will be turbulent, and in extreme impractical cases might even interrupt the current by pinching. If the height is too great, the flow of metal from channel to container is made difficult, possibly by overheating the metal.

The content of the container is approximately 80 to 100 times that of the channel, and in pouring is emptied about 60 to 80%, leaving a

liquid bath of 20 to 40% of the full content.   The height of the container is approximately two-thirds of the height of the channel for heavy metals and about four-thirds for aluminum   With increasing power of the furnace these values increase.

COILS

Since the coils are surrounded on all sides by liquid metal, they heat up.   Except at the ends, the coil is surrounded on all sides by metal. If it were not for the air cooling and the heat loss to the ends of the transformer, the coil would, in steady state, reach the temperature of the metal.   This is of course impractical and therefore cooling is applied, thus decreasing efficiency.   A transite tube on the inside of the bottom refractory forms the outside boundary of the air channel.   Great thickness of the bottom lining is desirable to decrease the heat flow to the transite tube and to decrease the cooling area which withdraws heat from the molten metal.   However, a thick lining reduces the available space for the coil and, by limiting the connected load, decreases the efficiency because of slower melting times.   A compromise solution must be found – usually in practice about 2½ in.; no systematic investigation of the optimum thickness has been published.

FURNACE SHELL AND TILTING MECHANISM

The furnace shell is made of heavy steel sheet welded or riveted to form a cylindrical or rectangular casing, and bolted to the bottom which may be a casing or made of sheet.   The top is open and covered only by a very lightly insulated cover which is taken off for charging.   The bottom casing provides ducts for the cooling air for the coil.   Usually tilting—by nose or center tilt—is effected hydraulically.

(d) Control and Electric Equipment

Unless extreme accuracy is required, core type melting furnaces are operated without automatic temperature control.   Attack of molten metal on the metallic walls of thermocouples makes their use impossible, and refractory tubes are often considered too sensitive for melt shop practice.   Control is carried out by changing the voltage in the channel, and this in turn is done by selecting taps on a control transformer.   Up to 25 taps, which allow a control from 5 to 120% of the full connected load, are provided.   Tap-changing switches are to be operated only after disconnecting the load by means of a contactor.

The furnace, because of relatively poor coupling between primary and secondary, has a power factor of only 0.60 to 0.80 for brass and of 0.40 to 0.70 for aluminum and light alloys.   External condensers compen-

sate for the low power factor so that the over-all power factor is brought up to 0.9 or more. Condensers are of the paper oil type and cause losses of approximately 0.3 w per kva at 60 cycles.

Instrumentation includes voltmeter, ammeter, wattmeter, watthour-meter, and possibly a power factor meter, the wattmeter being important for temperature control.

(e) Electrical Relationships

The power input in the secondary is expressed by Equation (59).

$$W_s = I_s^2 R_s \tag{59}$$

Notations.

W_s = power in secondary (w)
W_p = power in primary (w)
I_s = secondary current
I_p = primary current
R_s = secondary resistance
R_p = resistance of primary (ohm)
L_s = inductance referred to secondary

l_s = length of channel (secondary) (in.)
ρ_s = resistivity of molten metal (ohm cm)
A_s = cross-sectional area of channel (sq in.)
N_E = number of turns in primary
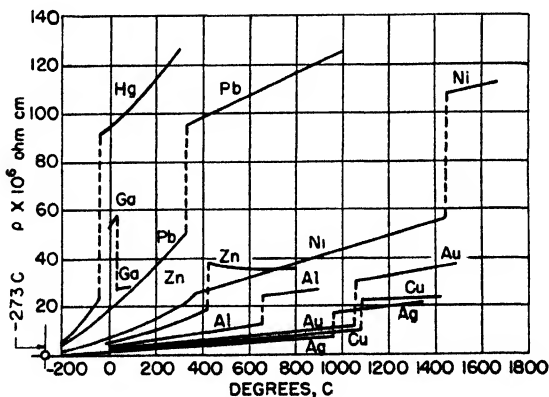
FIG. 215. Electric resistivity of metals.[76]

The resistance of the metal in the container being negligible as compared with that in the channel, the secondary resistance is practically entirely in the latter. Therefore:

$$R_s = 0.394 \, l_s \rho \, \frac{1}{A_s} \tag{60}$$

The secondary current, I_s, is induced by a current in the primary which is related to the former by the ratio of turns. The secondary having only one turn, the ratio equals N_E, and:

$$I_p = I_s/N_E \qquad (61)$$

Hence: $$W_s = (I_p N_E)^2 \times 0.394 \, l_s \rho \, \frac{1}{A_s} \qquad (59a)$$

The resistivity of metals changes with temperature and undergoes a rapid change at the melting point. In Figure 215 (page 239), resistivities (ordinates) are plotted against temperatures (abscissas).

The current in the primary causes ohmic losses, and therefore the energy in the primary is:

$$W_p = I_p(R_p + N_E^2 R_s) \qquad (62)$$

Because of the stray fields, the primary voltage is not directly proportional to the secondary voltage; voltage, current, and power are related by Equation (63):

Fig. 216. Power factor, power, and current vs. secondary resistance.[76]

$$W_p = EI_p \cos \varphi \qquad (63)$$

It can be proved that the power input is largest if the power factor $\cos \varphi = \sqrt{2} = 0.707$. Inductance of the circuit should therefore be so arranged as to yield this power factor.

$$\cos \varphi = \frac{R_s}{\sqrt{R_s^2 + (2\pi f L_s)^2}} \qquad (64)$$

The inductance, L_s, is almost constant, but the resistance changes with temperature and is different for various metals.

Figure 216 reveals that the input drops from the maximum more slowly for a power factor higher than 0.707 than for smaller power factors. Therefore the design should yield an inductance resulting in a power factor slightly larger than 0.707.

(f) Efficiency and Operating Data

In continuous operation, core type melting furnaces show energy losses in the form of: heat losses by conduction through the lining; heat losses by radiation from charging openings; electric losses in the primary; electric losses in the transformer core.

The heat losses are nonproportional and independent (see Vol. I, pages 64 and 65). The electric losses in the primary are in part proportional and in part dependent: part of the current in the secondary is used

to melt the metal; the equivalent part of the primary current causes proportional ohmic losses. Part of the secondary current is used to cover the heat losses, and the equivalent part of the primary current causes dependent losses. Similar conditions, although with different proportionality factors, exist for the core losses.

The relationships are shown in Figure 217 in a manner similar to Figure 144 in Volume I for arc furnaces. The cooling of the coil by air circulation is not considered. The amount of air depends somewhat on the electric load of the coil, but with increasing amount of air the heat losses through the lining increase slightly.

Typical power consumption figures for furnaces in continuous operation and full utilization of the furnace capacity can be read from columns *1* and *2* of Table XVIII; column *3* lists the pouring temperature and column *5* the approximate theoretical value of power consumption. From these figures an over-all efficiency is calculated and entered in column *5*. Neither a breakdown of these figures nor an energy balance has been published.
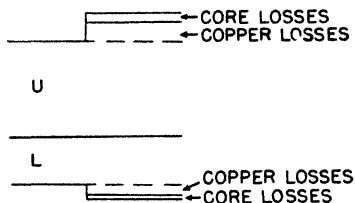
FIG. 217. Schematic energy balance of core type induction furnace: U, useful heat; L, heat losses.

TABLE XVIII

HEAT CONTENT, POWER CONSUMPTION, AND EFFICIENCY.
MELTING IN CORE TYPE INDUCTION FURNACES *

Metal	Power consumption, kwhr/ton	Pouring temp., F	Approx. theor. value, kwhr/ton	Approx. efficiency, %
1	*2*	*3*	*4*	*5*
Red brass (85% Cu)	250	2150	154	62.4
Yellow brass (66% Cu)	195	2050	128	70.8
Nickel silver (55 to 27% Zn)	275	2400	168	61.1
Bronze (95% Cu)	285	2150	163	57.2
Zinc	100	830	70.7	70.7
Aluminum	400	1260	267	66.7

* Based mainly on information supplied by Mr. J. Wyatt.

Furnaces of this type must not be allowed to freeze, or to be completely emptied except for repairs. Restarting is carried out by filling with liquid metal which has been melted in another furnace. If the production is not large enough to operate the furnace continuously, the furnace is idled overnight. The rate of idling losses is approximately 15% of the rate of power consumption at full production, so that, *e. g.*, for

yellow brass the following power consumption figures hold for noncontinuous operation:

Daily operation (hr)	Daily idling (hr)	Length of work week (days)	Consumption, kwhr/ton
16	8	7	210
16	8	6	217
8	16	6	215
8	16	7	233

Refractory life depends largely on the kind of metal produced and on the operating cycle. For yellow brass, for example, a lining may hold for from $3\frac{1}{2}$ months for small furnaces, up to 6 months for large. The cost of lining (Spring, 1946), depending on furnace size, is in the order of magnitude of 5 to 20 cents per 1000 lb of brass (including material and labor), and approximately $0.20 per lb of aluminum.

The great advantage of core type induction furnaces is the control of quality of the product. These furnaces were first developed for brass, where the necessity for elimination of zinc losses due to oxidation and evaporation offset any other economic consideration. Since heat is generated in the metal, no part of the metal surface is subject to overheating. If the container is large enough, the swirling action caused by electromagnetic stirring can be limited so that the surface of the metal pool remains relatively quiet; no excessive oxidation is caused. Internally energetic mixing occurs.

In aluminum furnaces the relatively large output from a furnace of moderate size, and the elimination of heat transfer from a hot cover (reverbatory furnace, resistance type furnace) are important advantages.

2. Coreless Melting Furnaces

(a) Applications

Almost any metal can be melted in coreless induction melting furnaces. The obtainable temperatures are theoretically unlimited, and practically limited only by the life and strength of the lining. Probably the most important application is that of steel, alloy, and carbon. Among nonferrous metals, nickel, nickel-chromium, red brass, bronze, gold, silver, and their alloys should be mentioned. The low outside temperature of the furnace shell makes the furnace well suited for vacuum and for pressure melting.

(b) Selection of Size and Shape

All crucibles for HFI (high-frequency induction) melting furnaces are cylindrical. The selection of the proper size depends largely on the

desired output. From experience, an over-all efficiency for the furnace is assumed; and after determining the useful heat (heat content of the metal at pouring temperature, including heat of fusion) one can find the connected load from:

connected load (kw) = output (lb/hr) × useful heat (Btu/lb)
  × (1/over-all efficiency) × 1/3413 kwhr/Btu

The over-all efficiency increases with generator size. For steel, the efficiency of small furnaces (50 to 200 lb) is in the order of magnitude of 40 to 50%; from 200 lb upward, between 50 and 55%.

After the generator size is selected, the size of the furnace proper follows from the desired melting time:

furnace size (lb) = output (lb/hr) × melting time (hr)

There are limits to the melting time. A lower limit is determined by the danger of overheating the active layer of the metal before it has time to transfer its heat to the interior of the charge. No melting time shorter than 20 min is practical. The upper limit is determined by the danger of excessive heat losses. Melting times longer than 2½ hr are ordinarily not recommended. Within that limit (20 min to 2½ hr) the power consumption increases but slightly with prolonged melting time. For example, Ajax Electrothermic Corp.[77] claims for a 100-kw generator, melting steel, a power consumption of 800 kwhr per ton for 20-min melting time and a power consumption of 825 kwhr per ton for 2-hr melting time.

After the furnace size, expressed in pounds, is selected, the diameter-to-height ratio is chosen. Several opposing factors influence the choice. *Great length* is desirable because of the lessened importance of the end effects of the coil and because of the smaller heat losses from the open top during stirring. *Great diameter* is desirable because the same amount of thermal insulation between crucible and coil decreases the electric efficiency less with large diameter than with small; because the tilting is easier for nonexcessive height of the furnace; and because of greater ease of observation.

Crucibles are usually not absolutely cylindrical but represent rather a frustrum of a cone, with an increase of diameter from the bottom to the slag line of 10 to 20%. In general the diameter at mid-height approximately equals the height. The coil is almost always cylindrical. The actual volume of the crucible is of course larger than that required by the molten metal, the excess height depending on the nature of the scrap to be charged. In a typical example the crucible had a volume 33% larger than the molten metal of the charge required.

[77] For example, *Metal Industries Catalog* (1945–1946).

(c) Selection of Frequency

The frequency of the current applied to coreless induction melting furnaces has been decreased over the years. The first furnace, designed by Northrup,[78] worked with spark gap generators, operating at from 20,000 to 80,000 cycles. About 1922, Northrup found that very much lower frequencies could be used—from 1000 to 3000 cycles. Although for melting purposes these frequencies are still the most widely used in the United States, the tendency in Europe has been toward lower frequencies. Poelzguter and Bardenheuer[79] work with furnaces of 500 to 600 cycles, and repeated attempts have been made to work without frequency transformation, that is, with the frequency of the supply system.[80]

Theoretically, there is a lower limit to the frequency. As explained, the rate of power input increases with the frequency. Particularly at values of $P_1 < 2.5$ the power increases with the square of the frequency. Hence, if, for a given diameter, the frequency is too low to permit sufficient power to cover the heat losses, obviously the furnace cannot operate.

Practically, the frequency is always selected larger than this minimum. Fischer[81] proved that, for a given frequency and a given resistivity of the charge, there is an optimum diameter, which results in the highest power absorption. This optimum diameter is:

$$d_{opt} = 1.8 \times 10^4 \sqrt{\rho/f\mu} \qquad (65)$$

From this equation it follows that the optimum diameter for copper ($\rho = 2.10^{-6}$ ohm $\times$ cm) is 3.6 cm at 50 cycles, 1.13 cm at 500 cycles, etc.

In melting furnaces these diameters refer to the size of the individual part of the charge rather than to the crucible, provided that the individual pieces are mutually insulated by an oxide layer. After they melt and thus coalesce, the diameter of the crucible would be the dimension to be introduced in Equation (65). The frequency for this new optimum diameter is lower. If the frequency does not change it should be selected to fit the furnace diameter. Before melting, and as long as the individual pieces are separated, they have a diameter smaller than the optimum. This is more desirable than having a diameter greater than optimum. It thus follows that large furnaces can be built with lower frequencies than

[78] E. F. Northrup, *Chem. Met. Eng.*, **17**, 685 (1917); *Trans. Faraday Soc.*, **13**, 213 (1917); *Trans. Electrochem. Soc.*, **37**, 69 (1919).

[79] F. Poelzguter, *Stahl u. Eisen*, **55**, 773 (1935). F. Bardenheuer, *ibid.*, **55**, 821 (1935).

[80] *Foundry Trade J.*, **40**, 141 (1929) (brass melting with 50 cycles in a coreless furnace). W. Rohn, *Stahl u. Eisen*, **54**, 77 (1934) (three-phase furnace for nickel-chromium; 50 cycles). G. Mars, *ibid.*, **58**, 833, 865 (1938) (steel melting with 25 cycles).

[81] W. Fischer, *Jahrbuch der drahtlosen Telegraphie u. Telephonie, Z. Hochfrequenztechnik*, **37**, 127 (1931).

small ones. If the frequency is very low, as in the case of the 25-cycle furnace described by Mars,[80] then the selection of proper size of charge becomes very important.

Frequency is also related to the bath movement. Since the forces acting on any one particle are inversely proportional to the square root of the frequency,[82] the bath will be more quiet at high frequencies than at low. For thorough agitation, lower frequencies are preferable, whereas a more quiet bath is obtained with high frequencies.
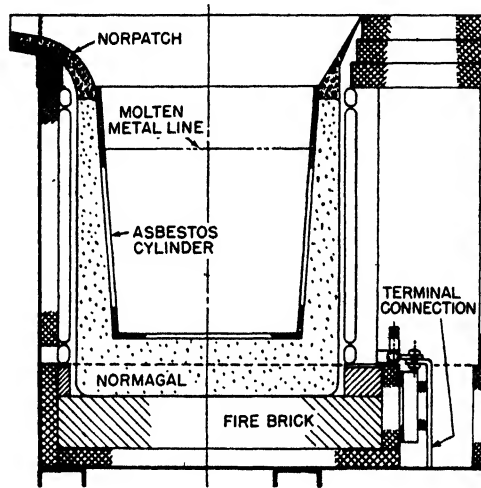
Fig. 218. Coreless induction melting furnace.
(Courtesy *Ajax Electrothermic Corporation*.)

(d) Design

Figure 218 shows the general arrangement of a furnace. The inside is bounded by an asbestos cylinder, which merely holds the lining prior to the first charge (see page 248). This cylinder is backed by a refractory lining reaching up to the coil which is enclosed in a nonmetallic rectangular box, held in a frame of brass angles.

COIL

Almost all coils in coreless induction furnaces are water cooled. They consist of copper tubing, with rectangular cross section and often with rounded edges. Figure 219 shows a photograph of a coil, Figure 220 two typical cross sections through the copper. In *a* one side is heavier than the other, in *b* all sides have equal thickness. As previously explained, only a small part of the copper, namely, a layer parallel to the

[82] W. Esmarch, *Wiss. Veröffentl. Siemens-Konzern*, **10**, 172 (1931).

inside surface of the coil and with a thickness equal to the depth of penetration, is carrying current.   The rest of the copper helps to support the current-carrying part and serves as a wall for the hollow through which the water is flowing.
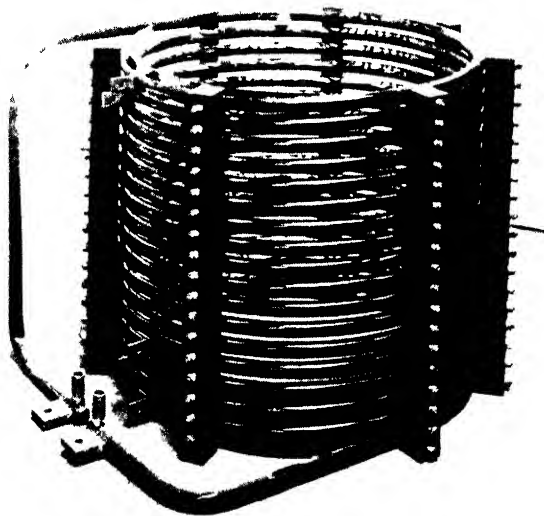
FIG. 219.   Coil for coreless induction furnace.
(Courtesy *Ajax Electrothermic Corporation*.)

The depth of penetration in copper is small, and, for example, at 10^3 cycles it is already smaller than $\frac{3}{32}$ inch (page 227).   Except for very low frequencies the wall of the copper tubing is almost always thicker than the depth of penetration.   Because of the less effective cooling, this is a disadvantage.   Heat must penetrate the non-current-carrying parts of the copper before reaching the water.   The coil should
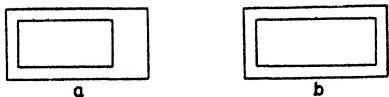
FIG. 220.   Cross section of turn of coil.

therefore be made as thin as possible.   For practical results the wall thickness is not more than twice the depth of penetration.

The turns of the coil are spaced as narrowly as possible, because the correction factor (j_R, page 227) depends on this spacing and influences the coil efficiency.   In Figure 219, the insulators supporting the coil permit it to stand up independently; it is not supported by the lining.   At the ends of the coils, water and electrical connections are provided.   Since the coil is kept cold, they offer no particular difficulty.

Special coils have been recommended by Esmarch.[82] They consist of several mutually insulated layers of thin copper strips wound about the crucible in the form of a vertical helix. The various layers are intertwined so that, for example, the layer innermost near the bottom of the crucible is further out at a higher level and, conversely, one of the outer layers near the bottom becomes the innermost layer at some higher level. Resistance, inductance, and relative position toward the charge are the same for all layers. Each strip is very thin, but the outermost layer (farthest away from the furnace) is always heavy, hollow, and water cooled. By heat conduction the inner layers are cooled too. The recommended thickness for each strip is a function of frequency and of the number of parallel layers. For four parallel layers and a frequency of 500, the recommended thickness is approximately 2 mm. The efficiency is claimed to increase considerably. The design has not been applied in the United States.

CRUCIBLE AND INSULATION

After the coil, the container for the metal is the most important part of the furnace. Great strength, low conductivity, and lack of interaction with the metal are the prime requirements for the container. There are several types of crucibles or containers in use: free-standing bilge crucibles, built-in preformed crucibles, and crucibles sintered in place.

Free-standing crucibles are used mostly for lower temperatures (nonferrous metals). Crucibles are either conducting, semiconducting, or nonconducting. Conducting crucibles are made of graphite; semiconducting, of a mixture of clay and graphite, or clay, graphite, and silicon carbide. When graphite is present, carbon pick-up by the charge is unavoidable if the metal is susceptible to carbon. (Most nonferrous metals are not.) Nonconducting basic crucibles are of electrically sintered magnesia with a small amount of bonding: acid crucibles are made of bonded silica. Neutral crucibles are made of zirconium. Conducting crucibles are used mainly for melting nonconducting materials such as oxides. When melting conducting materials in conducting crucibles the latter act as shields; and little or no current is induced in the charge, depending on frequency, nature of the crucible, and depth of penetration in the latter. Semiconducting crucibles act as a partial shield, but some current is generated in the charge proper.

The same kinds of crucibles, but with different shapes, are used for *built-in preformed crucibles.* The coil in these is first covered with a layer of refractory cement $\frac{1}{4}$ to $\frac{3}{8}$ in. thick. This layer is allowed to dry and harden. Then the bottom is built up by ramming in granular material until the level of the bottom of the crucible is reached. The

crucible is put into place and the space between the coating of the coil and the crucible is filled by granular material which is again rammed and filled to within ½ in. from the top of the crucible. A layer of air-setting cement seals off the granular filling. (The granular material should be tamped in tightly, avoiding air pockets.) The granular material surrounding the crucibles is usually of the same composition as the crucible: magnesia crucibles are packed in granular magnesia, silica crucibles in granular silica, etc. Clay–graphite and clay–graphite–silicon carbide crucibles are embedded in silica sand.

For *sintering crucibles* in place, a mold or form which governs the shape and size of the inside surface of the crucible is used. The coil is covered with a coating of refractory cement in the same manner as described for preformed crucibles. The spaces between the coating and the mold are rammed in with a suitable filler. The crucibles sintered in place can be made by one of several processes. They can be dry-rammed behind a form which holds its shape till sintering of the innermost layer is accomplished during the first charge. An asbestos sleeve is an example of such a form. Or they can be made of a form which is withdrawn before the first charge. Then the lining is moist or plastic during the ramming-in period and must air-set before the first charge is put in. The so-called Rohn's method utilizes a thin steel sheet mold, which may be heated by induction for prefiring the lining. In the first melt the sheet is melted with the charge which is thus less contaminated than when asbestos, etc., which appear in the slag of the first melt, are used. Rammed-in basic linings are usually a mixture of magnesium oxide and aluminum oxide; acid linings are made of ganister.

In small furnaces, prefiring of the crucible may be carried out without Rohn's steel sleeve, by inserting a graphite plug into the furnace, and using the plug as the boundary of the mold. After the lining is sufficiently hardened by heat transferred from the graphite plug, the power is switched off and the plug is withdrawn.[83]

The shape of the crucible has considerable influence on the life of the lining. Straight cylindrical types are rarely employed. But extension of the taper to different heights and amount of taper may vary, resulting in different life for the crucible. Doerrenberg and Broglio [84] have compared three shapes (Fig. 221). Actually achieved life expressed in numbers of runs is shown in Figure 222. The different runs were made with steels of different composition, and therefore only the averages should be compared. The superiority of shape III is obvious. The long life

[83] W. F. McKibben, *Trans. Am. Foundrymen's Assoc.*, **41**, 66 (1933).

[84] O. Doerrenberg and N. Broglio, *Stahl u. Eisen*, **50**, 617 (1930).

(82 melts) of the last crucible is not a random value, but was obtained by systematic efforts to melt carefully. The lining in this furnace was acid, made of Quarzit (silica sand), using Rohn's method.

The life expectancy of crucibles depends on a large number of variables, among which maximum temperature, intensity of bath circulation, duration of stirring period, nature and form of the charge, care in preparing the lining and care in charging are the most important.

FIG. 221. Comparison of three crucible shapes (Doerrenberg and Broglio).[84]

With this large number of influences, life expectancy figures are not very significant. Basic linings may vary from 60 to 800 heats, whereas acid linings may withstand from 20 to 80 heats.
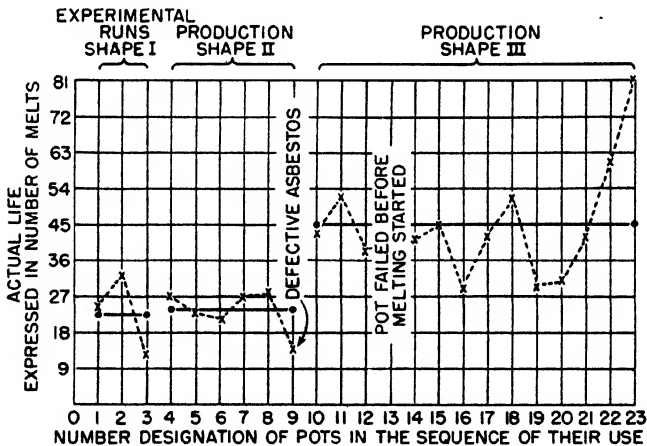
FIG. 222. Life of crucibles (Doerrenberg and Broglio).[84]

FURNACE BODY

The presence of stray fields surrounding the coil discourages the use of metals in designing the casing. Generally, magnetic materials are avoided entirely. With nonmetallic material, it is easier and more convenient to make the casing of a square cross section rather than cylindrical, with an attachment on one side to take up electric and water connections. The casing is usually made of asbestos board for small furnaces, or of wood covered with asbestos board for larger ones.

The angles and structural metal parts may be seen in Figure 223. Either nonmagnetic steel or bronze is used for metal parts. Some heat generation in these metal parts is unavoidable. In selecting the most suitable material it is possible to make use of Equation (65) on page 244. For equipment parts, the heat generation should be reduced, and therefore the "optimum diameter" should be avoided. For a given frequency this can be effected either by changing the diameter, or by selecting a material with a different resistance   Since the coil does not surround the bolts in the equipment in the way it surrounds the charge, these considerations are approximate only.
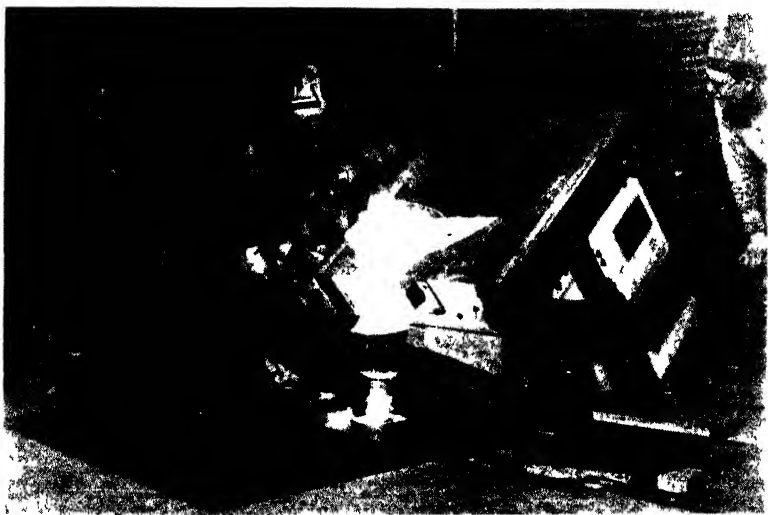
FIG. 223.   Outside view of coreless induction melting furnace.
(Courtesy *Ajax Electrothermic Corporation.*)

The design of the furnace shown in Figure 218 is typical for all high-temperature furnaces and many furnaces operating at lower temperatures.

Another design (Fig. 224) eliminates filler between crucible and coil. The coil, together with the outside shell and the charging hopper, can be readily removed from the crucible and transferred to another prepared base with another crucible. The crucible of the first furnace, with the metal ready for pouring, can now be lifted by means of a tongue or shanks and emptied into molds or forms. An overflow receptacle prevents metal from damaging the ceramic coating of the coil. The furnace body is connected with the bottom by means of a sand seal. The connections to the inductor coil are easily broken (see page 255).

Figure 225 shows the complete arrangement. Two bases with crucibles are built on a car which can move on a pair of rails between two definite limits or stops. In each end position one of the two bases is prepared to receive the furnace body with the coil. In the figure the one crucible is shown just prior to removal for pouring.

The simplicity of the induction furnaces, and the connector leads which are small as compared with those of an arc furnace, make the HFI furnace an ideal tool for melting under vacuum, under pressure, or in a special atmosphere.

FIG. 224. Arrangement of lift coil. (Courtesy *Ajax Electrothermic Corporation*.)

Of course the full utilization of the benefits of vacuum or pressure melting can be secured only if the pouring also occurs in vacuum. This

FIG. 225. Lift coil furnace. (Courtesy *G. F. Applegate Foundry*.)

can be accomplished (Fig. 226) by providing the mold or form together with the furnace in a gas-tight chamber. The entire chamber is tilted, and the furnace, being connected permanently to the bottom of the chamber, tilts with it. The mold or crucible is suspended from the walls of the chamber, and as the latter tilts, the mold because of gravity remains perpendicular. Water and electric connections are brought gas-tight into the chamber. The latter is provided with a detachable lid or cover which is tightened by pressure-tight bolts to the chamber and sealed by a gasket. Figure 227 shows a pressure furnace, with several observation windows. The spout, which is sealed pressure-tight, must of course be opened before pouring.

Both these special designs share the feature of nose tilt with all larger furnaces except the "lift coil" type of furnace. Nose tilting is provided because of the convenient location of the issuing metal stream. Tilting

is done either by electric or hydraulic lifting of the body of the furnace. Because of the great weight of the furnace, tilting around the center of gravity would mean less power for lifting. Therefore furnaces with two pivots have been designed which combine the advantage of nose tilt and center tilt. Tilting starts first at the center pivot (Fig. 228) and after a 30-degree turn is resumed by the nose tilt pivot. This method gives considerably more space in front of the furnace.
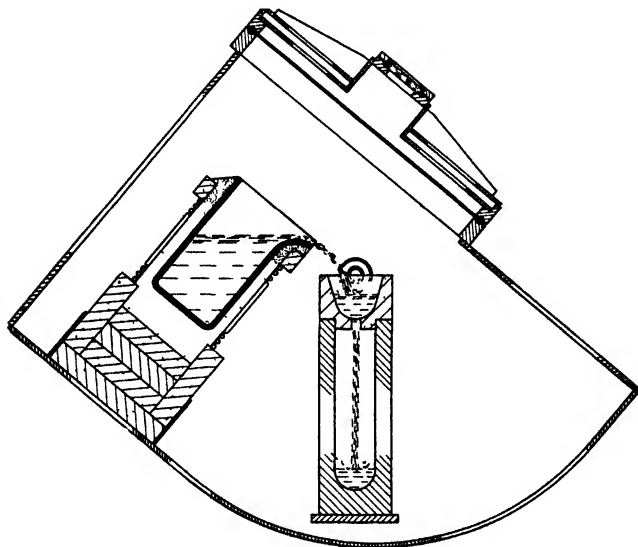
Fig. 226.   Vacuum furnace.   (Courtesy *Ajax Electrothermic Corporation.*)

ELECTRICAL EQUIPMENT

The electrical equipment, looking from the coil to the power supply, comprises: means of connecting the coil to the busses; busses; condensers; control panel; generator or power supply. The latter is not discussed here (see page 214). Melting furnaces are usually equipped with motor generator sets or mercury-arc converters except for sizes below 50 kw, in which tube generators or spark-gap oscillators prevail.

The coil may be connected to the busses by means of a flexible cable or a cutoff knife switch which automatically opens the circuit when the furnace is tilted (see Fig. 230, page 255).

Condensers are required because the power factor of the furnace proper is always low (see page 232). The generator is the most expensive individual item of a furnace assembly; its size must be selected on the basis of the total current, not of the in-phase part of the current. Hence it is very important to compensate the power factor to unity by
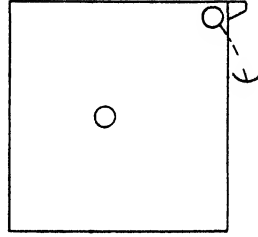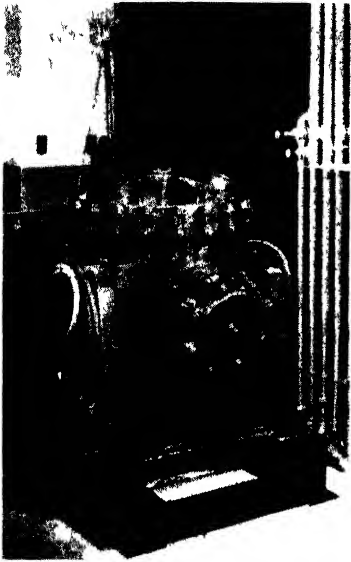
FIG. 228   Double pivot tilting.

FIG. 227.   Pressure furnace. (Courtesy *Ajax Electrothermic Corporation*.)

means of condensers.   With a power factor of 0.1, a 1200-kw furnace requires approximately a 12,000 kva condenser bank, and with a power factor of 0.05 a bank of approximately 24,000 kva.   The condensers used are of the paper oil type and are water cooled.   They have an internal loss of approximately 2.5 w per kva, and therefore with a 12,000-kw furnace would dissipate some 30 kw.

The power factor of the furnace changes during each load because resistivity, with magnetic materials, changes during each charge.   The required capacitance changes accordingly, and therefore condenser banks must be designed for easy changing of capacitance.

Figure 229 shows a set of condenser units.   The heavy bus connects one pole of all condensers, whereas the other pole is brought out in several taps to allow change of capacitance.   The cables leading to the contactors are seen behind the bus bar, and the hose for connecting the cooling water is in front.

When the frequency of the power supply is not fixed, but changes with the change of resistivity and permeability of the load, as is true with mercury-arc converters, capacitance need not be changed during the operation.   In such cases condensers without taps are used, and the contactors described hereafter are not required.

Contactors are used to change the capacitance during each run of the furnace.   This "tap changing" is done without load; the furnace is switched off, before the tap changing occurs.   Contactors for high fre-

quency must be designed differently from those for 60 cycles.[85]   This is particularly true for such contactors as have to be operated under load. Such contactors, at normal frequencies, have a blowout coil which extinguishes the arc. Since the high impedance of this coil would lead to overheating during periods when the contactor is closed, special arrange-
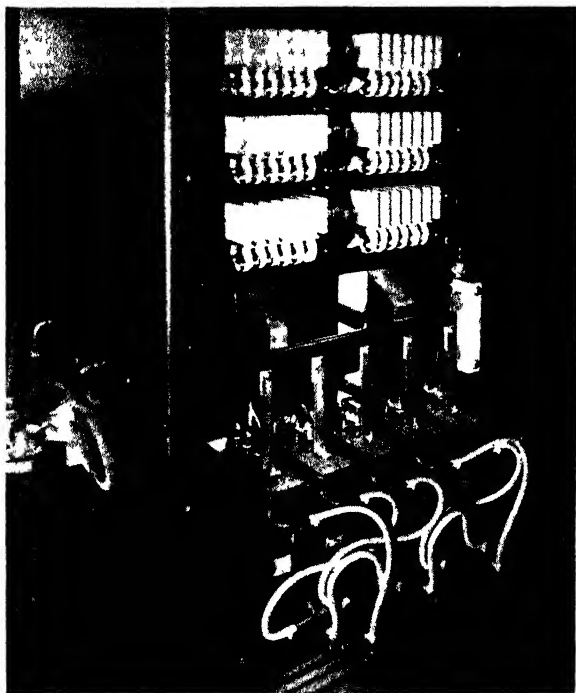
FIG. 229.   Condenser units for high frequency. ·
(Courtesy *Ajax Electrothermic Corporation.*)

ments are made to put a blowout coil in the circuit only at the moment of operation.   Large contactors may have water-cooled contact tips and shunts.

The permissible current decreases quite rapidly with increasing frequency—approximately with the fourth root of the latter; the permissible current at 5000 cycles is only about $1/\sqrt[4]{10} = 0.57$, of the current permissible at 500 cycles.

The control panel contains instruments for the motor side, but in addition, for the high-frequency side, voltmeter, ammeter, wattmeter, and power-factor meter.   With motor generators as power supply, it is

[85] F. E. Ackley, *Ind. Heating*, **11**, 538 (1944).   C. C. Levy, *Elec. Eng.*, **53**, 43 (1934).

important to know the power factor, in order to change the capacity so that a power factor equal to 1 on the generator is always obtained.

(e) Complete Furnaces and Plant Layout

Of a total furnace installation the furnace proper, including crucible, coil, and shell, with or without tilting mechanism, is very much less expensive than the electrical equipment, particularly the power source and the condensers. Therefore frequently two complete furnaces are provided for one set of electrical equipment.
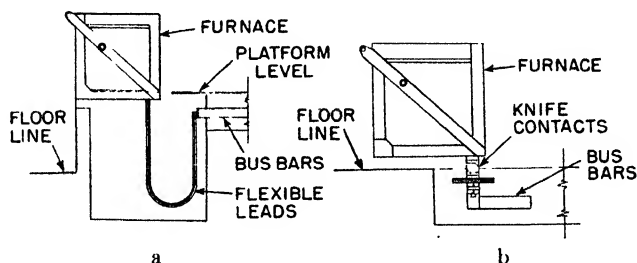
FIG. 230. Arrangement of furnaces for pouring.
(Courtesy *Ajax Electrothermic Corporation*.)

Generally, leads should be as short as possible, particularly between condensers and furnace. Emptying of the furnace can be done by one of two methods (Fig. 230). The furnace may be mounted on a platform, and the molds put on the floor below the furnace (Fig. 230a); flexible cables permit tilting. Or the entire furnace can be picked up by a crane or hoist and carried anywhere in the shop (Fig. 230b). Knife contacts permit separation of the furnace from the power supply.

The furnaces as described above are the most commonly known in the United States. In a Swedish design,[86] parts of laminated cores surrounding the coil improve the power factor (Fig. 231).

Rohn[87] worked with three-phase furnaces, giving the crucible a shape more closely resembling that customarily used for arc furnaces. Power is transferred to the bath by means of pancake coils applied from the outside to the crucible and connected to the three phases of the power supply system. Part application of cores A, again improves the power factor and reduces the size of the necessary condenser battery (Fig. 232).

Dreyfus[88] has described a furnace operating at two different frequencies. Because application of high frequencies means increased power input, but provides less stirring action, his furnace *melts* with high fre-

[86] F. Poelzguter, *Elektrowärme*, 6, 38 (1936).
[87] W. Hessenbruch and W. Rohn, *Stahl u. Eisen*, 54, 77 (1934).
[88] L. Dreyfus, *Jernkontorets Ann.*, 118, 162 (1934).

quencies; as need for intensive *stirring* during the refining period occurs, power at supply system frequency (50 cycles) is applied.

FIG 231   Furnace with laminated core.
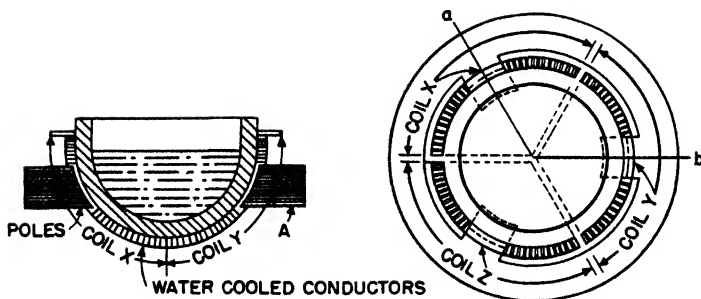
FIG. 232.   Furnace with pancake coil.

(f) Energy Balance and Operating Data

The few energy balances published on coreless induction type furnaces[89] do not distinguish between dependent and independent losses nor between proportional and nonproportional losses. The diagram (Fig. 217) shown for core type induction furnaces may be applied to coreless furnaces, up to and including the inductor coil. Losses in the generator and in the condensers are to be added. The losses in the generator may again be assigned in part to the heat losses and in part to the useful heat. The condenser losses, however, are independent (Fig. 233). U represents the useful heat in the metal, L the heat losses. C_U and C_L are the losses in the coil, caused by the parts of the current for useful heat and losses

[89] See references in Table XIX.

respectively; G_U and G_L are the equivalent part of the losses in the generator, and CAP indicates the energy loss in the condensers.

If metal with different specific heat or heat of fusion is melted, but heated to the same temperature, then U will change, but L will remain unchanged.   Because of the different heat in the furnace, the ratio of $(C_U + C_L)/(U + L)$ may change.   But, independent of this change, the ratio of C_U/C_L will be different from the previous value.
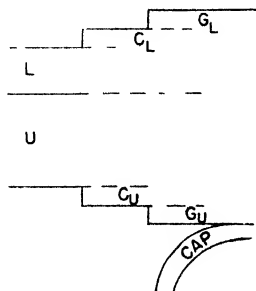
Fig. 233.   Efficiency diagram for coreless induction furnace.

A similar diagram should be drawn for each set of circumstances to give the efficiency figures significance.   Since more systematic investigations are lacking, the figures in Table XIX may be of interest.   Furnace

TABLE XIX
ENERGY BALANCE OF CORELESS INDUCTION FURNACES

Item of power consumption	110-lb (50-kg) furnace[a] $f = 6900$	1-ton furnace[b] $f = 500$	4-ton furnace[c] $f = 500$	1430-lb (650-kg)[d] $f = 25$
Useful heat	21.9	62.7	68.9	57.1
Generator	34.2	24.4	16.0	—
Busses and condensers	7.7	2.7	3.5	—
Coil losses	9.2	4.2	8.2	20.3
Heat losses	27.0	6.0	3.4	22.6
Total	100%	100%	100%	100%

[a] F Wever and W. Fischer, *Mitt Kaiser-Wilhelm Inst. Eisenforsch. Düsseldorf*, **8**, 149 (1926).
[b] F Poelzguter, *Stahl u. Eisen*, **51**, 513 (1931).
[c] F Poelzguter, *Electrowärme*, **6**, 38 (1938); *Stahl u. Eisen*, **55**, 773 (1935).
[d] G Mars, *Stahl u. Eisen*, **58**, 833, 865 (1938).

a is quite old and was one of the first built in Europe.   Furnace d is for very low frequency.   Furnaces b and c may be considered more nearly representative.

Power consumption of furnaces built in this country ranges approximately between 650 and 850 kwhr per ton for steel melting according to furnace size; 375 to 480 kwhr per ton for red brass; 600 kwhr per ton for aluminum; 14 whr per oz troy for gold; 10 whr per oz troy for silver.   Water consumption is of the order of magnitude of 1–1.25 gal/lb

of steel and about half that amount for brass, the water being used in the coil, the condensers, contactors, and possibly in the terminals.

Clean air for cooling of rotating motor generators is required at high rates, ranging from 1200 cfm to as much as 25,000 for relatively large low frequency (500 cycles) units.

C. Heating Appliances

While induction melting is always carried out in furnaces, heating is as yet almost always carried out in "appliances" (see page 1); no well insulated furnace chamber is provided, although sometimes a slight insulation is used.

1. Low-Frequency Appliances

Whereas melting furnaces were logically divided into core-type and coreless furnaces (the latter being mostly operated with high frequencies, and only occasionally with 60 cycles), the appliances are more conveniently divided on the basis of frequency. Low-frequency appliances with and without core are relatively similar in design and in application.

For heating to temperatures below the Curie point, induction heating with 60 cycles is practical. Applications of this kind of heating include stress relieving, particularly in welding operations, preheating for arc welding, heating of containers in the chemical industry, and occasionally heating of pots of salt bath furnaces for low-melting salts. Because of the high magnetic resistance of air at low frequencies, the magnetic flux is always conducted at least in part within a ferromagnetic metal. A core may be provided or, when heating steel, the charge itself may carry not only the electric current but also the magnetic flux.

Since the voltage applied to the inductor coil is low and must be easily adjustable to different operating conditions, a stepdown transformer with several taps is frequently used.

The simplest design of a low-frequency appliance comprises a cylindrical coil surrounding a pipe. Asbestos-insulated cables may permit placing the windings close to the pipe surface. For temperatures in the order of magnitude of 600 to 1200 F the voltage to be impressed on the coil may be estimated to be 0.08 to 0.12 v per in. circumferential length of the coil. Actual voltages range from 5 v or less for small pipes to several hundred volts for large pipes.

Heating pipes from the inside (Fig. 234) is somewhat more difficult, because the current tends to concentrate near the inside surface of the coil, away from the pipe surface. It is desirable and important to place the coil as close as possible to the inside cylinder surface. Also winding the coil on a magnetic core has been applied successfully.

For large or irregular surfaces "pancake" type coils (Fig. 235),

which cover a part or all of the surface, are used.   The figure shows as
an example a drum which should be rotated during heating in order to
obtain uniform temperature in spite of the localized generation.   With
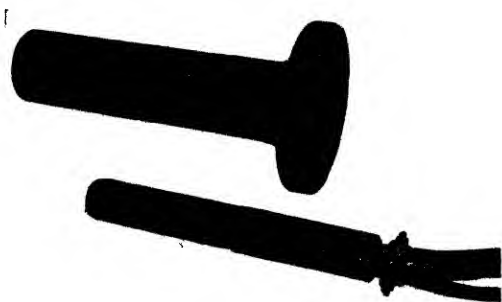
FIG. 234.   Core and coil for internal pipe heating.
(Courtesy *Electric Arc, Inc.*)
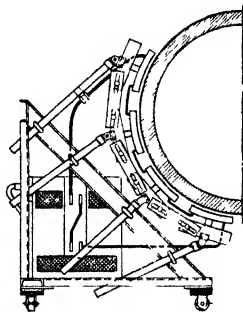
FIG. 235.   Pancake type
heaters applied to drum.
(Courtesy *Electric Arc, Inc.*)

pancake coils the use of cores is particularly desirable.   Figure 236 shows
schematically the arrangement.   The path for the magnetic flux is closed
through the steel sheet, which is to be heated.   The charge thus forms
an electric resistor and a magnetic conductor simultaneously.   With a
given number of turns of the primary coil a certain secondary voltage
is impressed on the charge, and this in turn causes flow in the charge.
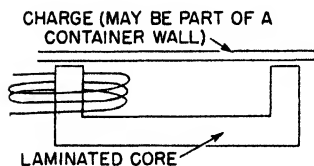
FIG. 236.   Core type low-
frequency induction heating.
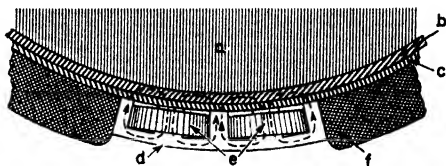
FIG. 237.   Copper plating of charge: *a*,
charge; *b*, copper plated boiler plate; *c*, asbestos;
d, laminated core; *e*, induction coil; *f*, thermal
insulation.[90]

Because of the magnetic saturation of the core, a minimum number of
turns in the coil is required, thus placing an upper limit to the secondary
voltage.   The secondary voltage, finally, determines the useful power.
This apparent limitation can be overcome by increasing the conductivity
of the charge.   The steel sheet to be heated is copper plated for this
purpose.[90]   In Figure 237, the "charge" is a container for a liquid, *a*.
The steel behind the copper plating closes the magnetic circuit, but the

[90] H. Staack, *Elektrowärme*, **7**, 148 (1937).   O. Neiss, *ibid.*, **11**, 106 (1941).

heat is generated mainly in the copper layer.   Because of its high con-
ductivity the power consumption is high.   The power factor increases
also, because the inductance of the coil is not changed, and is compensated
by a larger resistance.   Figure 238 (from Neiss [90]) shows the increase in
power as compared with a unit without copper plating.   At the optimum
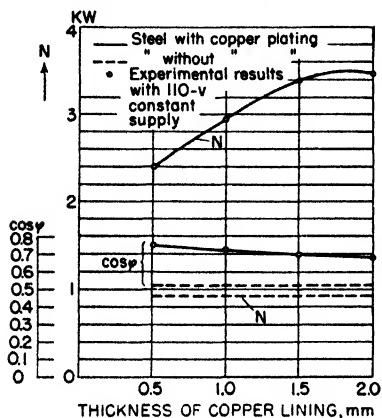
Fig. 238.   Power absorption for copper-plated steel plate.[90]

thickness of the copper (1.8 mm = 0.07 in.) the copper-plated material
absorbs four times as much power as the nonplated.   The steel itself
must be thick enough to carry the magnetic flux, and the core must be
pressed thoroughly against the sheet.

2. High-Frequency Appliances

(a) Applications

The most important characteristics of high-frequency induction
heating in regard to its application are: possibility of generating heat in
reasonably localized areas at very high rates; generation of heat in the
piece itself, which simplifies the duplication of results once achieved; rela-
tively low efficiency, which limits the usefulness to heating of relatively
small masses, or to applications in which other extreme advantages more
than offset high power costs.   The "small masses" refer to the part ac-
tually heated; if, for example, the teeth of a large gear are surface hardened
by induction, only a thin layer of steel next to the surface is heated.   The
balance of the gear remains cold, and its mass does not contribute to the
power consumption and is therefore unimportant in the induction heating.

Actual applications can be grouped into "surface heating" and
"through heating" jobs.   The former are particularly important and find
their widest range of application in hardening and brazing.   Only a few
of the many which have been described can be mentioned.[91]   Hardening

[91] H. B. Osborn, *Trans. Electrochem. Soc.*, **79**, 215 (1941); *Metallurgia*, **24**, 61 (1941).

applies to regular or irregular surfaces to be hardened in part or completely. It also includes hardening inside surfaces of hollows. Brazing and soldering frequently can be carried out in such a manner as to melt only the soldering metal, without appreciably increasing the temperatures of the soldered or brazed parts. A particular method of hardening peculiar to induction heating is called "self-hardening." Hardening is usually carried out by heating and subsequent quenching in oil, water, or brine. Induction heating allows such rapid heating of a thin layer next to the surface that upon disconnecting the current the steel layers adjacent to the surface cool the surface layer rapidly enough to produce the desired hardness, without application of a liquid quenching medium.

The field of surface heating includes the heating of the metal parts in vacuum tubes in order to evacuate the tubes, and the heating of metal parts for sealing them into glass. Also of interest is the application of tinning.[92] Steel strip is so rapidly heated under an induction heater, that the applied tin barely comes to the melting point. Thus it is possible to use an electrolytically deposited layer of tin which results in a thinner and more uniform coat than by conventional heating methods.

Through heating includes mainly heating for annealing and for forging, the economic justification for the latter application being the rapidity of heating and consequent lowering of scale formation.

(b) General Description

An induction heater consists, mechanically speaking, of the power supply and the applicator coil. Power supply and coil should be in close proximity to avoid inductive losses in the leads. Therefore the coil is usually put directly on the terminals of the power supply. Since the coil is generally interchangeable, a clamping device which permits rapid changing of the coil is provided. For hardening purposes the quenching device, usually built as an integral unit with the heater, is important. Application of protective atmosphere and conveying mechanisms represent additional features.

Because it is necessary to bring a highly specialized electric tool (the power supply) into the shop, the units are well enclosed in a cabinet, and the only parts directly accessible are the terminals for connecting the coil, and the controls, which ordinarily include a starting switch and tuning devices for power control, and possibly capacitor selector switches. A typical installation is shown in Figure 239. Before describing the coils and accessories, the problem of selecting input rate and frequency for induction heating will be reviewed.

[92] H. C. Humphrey, *Electronics*, **16**, 69 (1943).
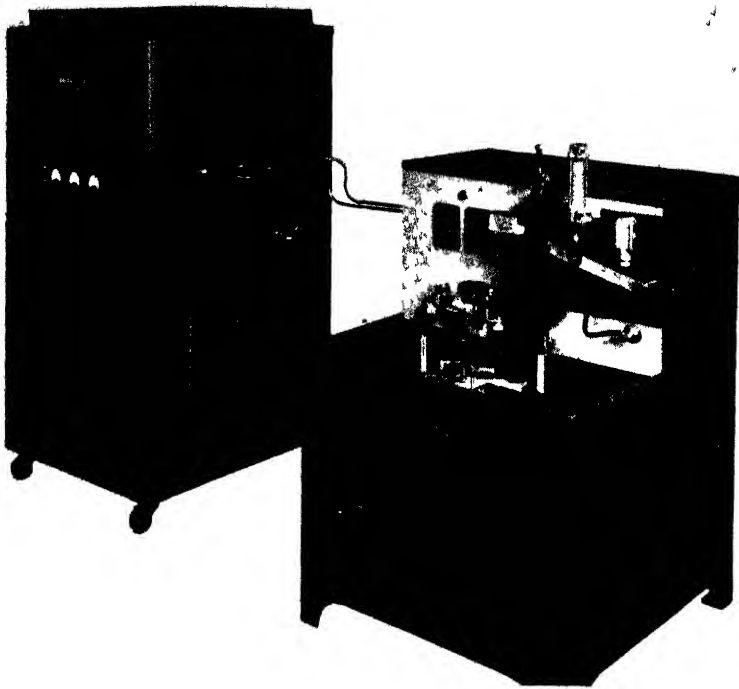
FIG 239   Thermionic Generator and single position automatic table with Oil Quench for hardening variable pitch propeller hub raceways (Courtesy *Induction Heating Corporation*)

(c) Input Rate and Frequency

Induction heating occurs in a thin layer near the surface.   The layer is thinner for higher frequencies than for lower   To study the influence of input rate and frequency, two cases must be considered separately—one of through heating the metal, as for annealing or forging; and the other for heating only a small part near the surface, as in hardening or brazing.

THROUGH HEATING

Unless the section is extremely thin, the heating effect can be considered to take place "at the surface."   In other words, an infinitely small "depth of penetration" is assumed.   Figures 5–12 (pages 9–17) can be referred to for determining the surface and center temperatures.   The charts are applicable for constant properties (thermal conductivity, volumetric specific heat) and for a constant rate of energy input.

The temperature function for induction heating, y_I, is defined by:

$$y_I = \frac{t_s - t_a}{q/h} \qquad (66)$$

where t_s = surface temperature at the end of heating (F), t_a = ambient temperature = initial charge temperature (F), q = rate of heat flow (Btu/sq ft, hr), and h = boundary conductance (Btu/sq ft, hr, F). Obviously y_I is also dimensionless. The same value of y_I should be introduced in the rate charts. The uniformity charts (Figs. 2–4, pages 5, 7, 8) do not involve the value of the furnace temperature and can be used without further difficulty.

If, in through heating, the piece is very thin, or the frequency very low, the assumption of heating only the surface is no longer valid, and the charts cannot be used. The correct values will lie somewhere between those obtained from the above charts, based on the assumption of a pure surface heating, and those for dielectric heating (page 295), where it is assumed that the heat is generated uniformly over the cross section of the material. The values will be closer to the "induction values" (Figs. 5–12) for higher frequencies and greater thickness and closer to "dielectric values" for lower frequencies and smaller thickness.

A theoretical limit for the maximum surface temperature in through heating is given by the condition in which the entire generated heat is used for covering the heat losses:

$$t_{s_{max}} = q/h \qquad (67)$$

The value of h can be calculated, assuming that heat is lost by radiation only, that the material has an emissivity of one, and that radiation occurs against an unlimited surrounding of a constant temperature of 70F. In Figure 240, h is plotted for these conditions against t_s. The second curve shows q_{min} for different temperatures; the values of q_{min} have been determined by multiplying the ordinate value h for each abscissa value,
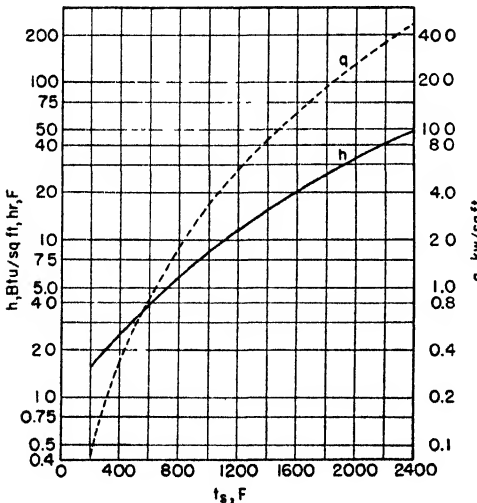
FIG. 240.   Minimum rate of power input as function of temperature.

t_s, by the related value of t_s. Should the emissivity be smaller than one, the ordinates, h, in Figure 240 are to be multiplied by the emissivity.

Heating time with an input rate of q_{min} to temperature t_s, would be infinite; the efficiency when heating even to a temperature near that value would be impractically low. Therefore the actual q should be very much higher, at least twice the amount of q_{min}.

The figures for power input are given for no heat insulation. For through heating, a heat insulation can be placed between the charge and the coil, and—neglecting end effects—the value, h, in Equation (66) should be replaced by k/D, where k is the thermal conductivity of the insulator and D its thickness. With these values a graph similar to Figure 240 is easily plotted.

SURFACE HEATING

Heating of a thin layer near the surface is desired for hardening, soldering, and brazing. Frequently the two latter applications are not particularly sensitive to great heat penetration. In hardening processes, however, too great a heated zone may destroy the entire desired result. The very rapid heat extraction from the heated zone toward the interior permits limitation of heating to a narrow zone near the surface only when the heating cycles are very short; short heating cycles require high energy densities.

For such short heating cycles, during which the inside of the body remains cold, the heating of the surface progresses as in a semi-infinite body; this rule applies, provided that the frequency is high enough to permit considering the heat source as limited to the surface. Such an assumption may be invalid for two reasons: first, in very short times the sections subject to heat flow are extremely thin, and may therefore approach the order of magnitude of the depth of penetration; and secondly, when heating magnetic materials, the zone of heat generation shifts as the material heats beyond the Curie point. Osborn [93] and Cable [94] suggest superimposing the skin effect and that of heat flow (Fig. 241). Curve AC shows the depth of penetration for a given set of conditions. The curve is also marked "theoretical value of zero time" because if no heat flowed toward the inside of the piece and if by external application of a coolant the entire heat from the "penetrated depth" could be withdrawn suddenly, the piece would be hardened to a depth as shown on the abscissa. Because of heat flow, however, a larger section will be heated, and thus the second curve, BD, is obtained. The lag indicated by the distance A–B and C–D, respectively, is caused by heat flow into the

---

[93] H. B. Osborn, in *Induction Heating*. American Society for Metals, Cleveland, 1946, p. 1.

[94] J. W. Cable, in *Induction Heating*, p. 101.

piece, which depends on the time neces-
sary to heat the "depth of penetration."
If the rate of input is 12 kw per sq in.,
the depth of penetration 0.02 in., the area
receiving energy from the coil 1.2 sq in.,
and the heat necessary to raise the tem-
perature to the desired value 1.2 kwsec
per cu in., the input to the piece is
$12 \times 1.2 = 14.8$ kw; the volume is 0.02
$\times 1.2 = 0.024$ cu in.; the necessary
energy is $1.2 \times 0.024 = 0.0288$ kwsec;
and the theoretical heating time is
$0.0288/14.4 = 0.002$ sec. During this
time, heat has penetrated perhaps 0.01
in. into the body, because of heat flow.

Fig. 241. Depth of penetration and
zone of heating by conduction.[93]

The curves shown in Figure 241 apply to one energy density: by
increasing the density, the two curves, A–C and B–D, are brought
closer together. In this way the minimum depth that can be hardened
is decreased. However a limit is set by metallurgical considerations. If
the time required to avoid undue heat flow to the inside is too short, it
may not be sufficient to perform the necessary metallurgical changes in
the structure of the steel. Osborn [93] presents a table (see Table XX) on

TABLE XX

DEPTH OF HARDNESS

Frequency, cycles/sec	Min. practical depth of hardness (in.)
3000	0.060
9600	0.040
120000	0.030
500000	0.020
1000000	0.010

minimum depths in hardening steel. He does not specify the steel for
which the table applies, nor the energy density used.

Figures 242 and 243 may serve as examples for recommended power
input (kw/sq in.) as function of bar sizes (round steel) for different desired
depths of hardening and frequencies. Figure 242 holds for 0.100 to 0.150
in. depth at 9600 cycles or 0.18 to 0.2 in. at 3000 cycles, whereas Figure
243 (note smaller diameters) holds for a desired depth of 0.040 to 0.050 in.,
to be obtained with 375 to 550 kilocycles.

In cooling from an external quenching source, heat conditions somewhat similar to those by radiant heating prevail. If the body is too thick, hardness cannot be achieved. Conditions are, however, always in that respect better for induction heating than for an external heat source,
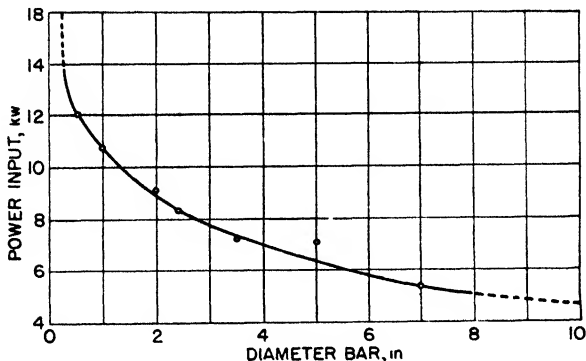
Fig. 242.   Recommended minimum rates of power
input (bars 0–10 in.).[93]
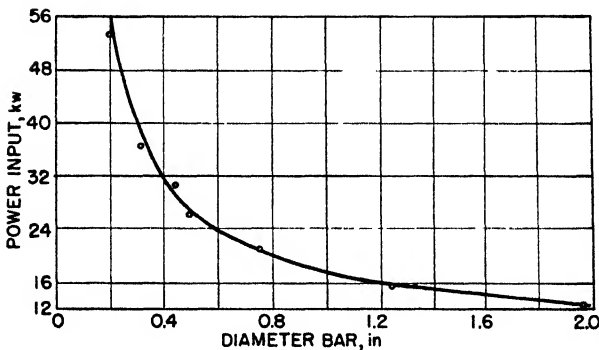
Fig. 243.   Recommended minimum rates of power
input (bars 0–2 in.).[93]

because if only surface hardening is desired the heat penetration may be kept smaller than in external heating. Successful heating has been reported so often that the references [95] below are given at random.

The problem of self-hardening or self-quenching is much more complex. If the heat input is high enough and localized enough, it is possible to use the withdrawal of heat into the metal as a means of rapidly lowering the surface temperature. Conditions would be reasonably simple if the "inside" were at room temperature at the moment when quenching

[95] G. C. Riegel, *Metal Progress*, **44**, 78 (1943).   F. W. Curtis, *Tool Engineer*, **13**, 18 (Feb., 1945); *Steel*, **111**, 72 (1942).

starts. Actually it will be at higher temperatures. Conditions have been analyzed by Roberds.[96] Power requirements are extremely high, of the order of magnitude of 50 to 100 kw per sq in., and the necessity for concentration of the power within a limited area is a major difficulty in coil design.

Figure 244 contains three graphs that hold for heating with $f = 500,000$ and an energy density of 100 kw per sq in. The graphs are for different times elapsing after application of heat: 5×10^{-5} sec (A); 1×10^{-2} sec (B), and 5×10^{-2} sec (C). In Figure 244A, the Curie point
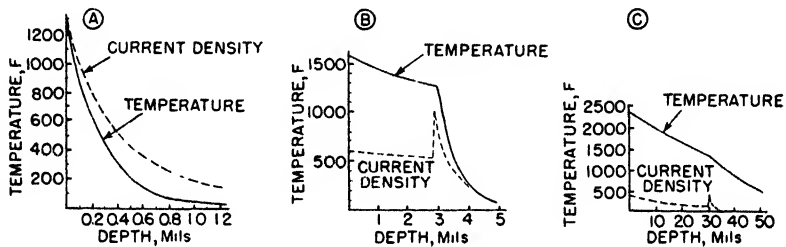
Fig. 244. Temperature and heat distribution in surface heating.[93]

has not been exceeded; the current density curve is smooth. In Figure 244B, the Curie point was reached at a depth of approximately 3.1 mils; consequently the current density curve has a discontinuity at this point; similar conditions prevail at 30 mils (Fig. 244C).

(d) Coil Design

SURVEY OF PROBLEM

For use in melting furnaces, coils and charge are usually cylindrical. In induction heating appliances, however, the charge may have all sorts of shapes and forms. Sometimes the charge is to be heated through, but more often a limited layer next to the surface is heated. For each set of conditions special coils must be designed. Before the different coils are discussed, the general principle underlying their design will be briefly examined. Generally, close coupling should be obtained between the coil and the charge. For a charge enclosed in a coil this is a well defined problem—the closer the outside diameter of the charge is to the inside diameter of the coil, the better is the coupling and the electric efficiency (see page 227). Due attention must be given to the length of the coil.

The coil design should include such factors as coupling between coil and work, the energy density in the workpiece, and the voltage. In the previous section the energy density in watts per square inch was discussed. The coil is the means by which the desired density is actually

[96] W. M. Roberds, *Proc. Inst. Radio Engrs.*, **33**, 9 (1945).

obtained.   If the desired rate of power input is obtained but spreads over too large or too small an area of the workpiece, an energy density other than that desired may result.

If a wire (or a hollow tubing) is placed above a plate, and high frequency is passed through wire or tube, a current is induced in the plate not only immediately below the conductor but also at some distance. However the peak of the current occurs directly below the conductor and is more pronounced if the wire is close to the plate. Conditions are illustrated in Figures 245 (geometric arrangement) and 246 (current distribution).

The total current induced in the plate equals the area under the distribution curve.   Brown[97] determined also the current distribution on the wire and established values of electric efficiency.   In a single inductor wire over the plate, the electric efficiency depends on the ratio $d/2H$ rather than on that of r/r_1 used for concentric coils.

The electric efficiency is plotted in Figure 247 for various values of resistivity

Fig. 245.   Geometric arrangement.[97]

ratios.   To obtain a given power input, voltage and current must be increased, and if the voltage becomes too high, the danger of flashover between coil and charge becomes serious.

In practice in many instances there will be not just one conductor, but rather a pancake coil parallel to the plate.   The current distribution in the plate will be flatter, and the efficiency will be higher and the voltage lower than with a single wire.   If very concentrated energy (high density on limited area) is required, application of only one wire may be necessary.
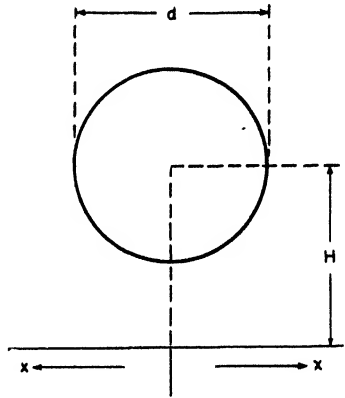
COILS FOR CYLINDRICAL PARTS

Very high energy densities may necessitate making the coil a single conductor coil.   Otherwise no special conditions prevail, thus permitting the use of normal coils consisting of flat or circular tubes.   It is desirable to space closely the turns of the coil; the individual turns are "reproduced" in a heat pattern on the charge, particularly where close coupling is applied.   If a small pitch of the turns is not sufficient, the charge may be rotated to obtain more uniform heating.

[97] G. H. Brown, *Electronics*, **17**, 124 (1944).
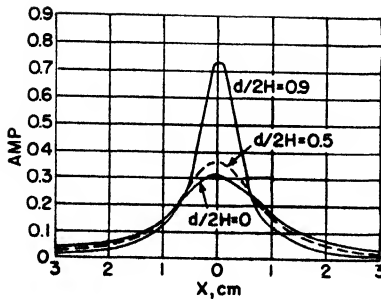
FIG. 246. Current distribution in conducting sheet for conductor of finite radius and $H = 1$ cm. [97]
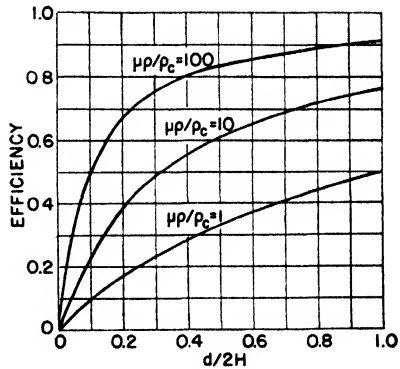
FIG. 247. Efficiency curves for single-wire heating of plate. [97]

COILS FOR SPECIAL SHAPES

The number of special shapes of coils is so great that no systematic presentation is practical.   Some examples are offered here and reference is made to complete descriptions. [98]

Figures 248A, B, and C illustrate coils for local hardening; next to each coil the piece to be hardened is shown.   For conical pieces the spacing of the turns near the thinner end must be closer together (Fig. 249).   In this way the poorer coupling, caused by the less favorable ratio of radii at this end, is offset by a greater number of turns per unit axial length, and uniform heat may be obtained.   Another solution is a conical coil, parallel to the surface of the charge.

Pancake coils tend to heat more intensely toward the center.   In order to offset the influence of this greater intensity, the distance between coil and charge should be greater at the center than at the perimeter; thus a more uniform temperature is obtained on the plane surface (Fig. 250).

FIG. 248.   Coil shapes. [98b]

An ingenious device is shown in Figure 251; the coils permit continuous feeding of the charge to the coil; the charge consists of condenser cans, the bodies of which are to be soldered by HFI heating to the base. The assembly, placed on a belt, is moved through the coil.
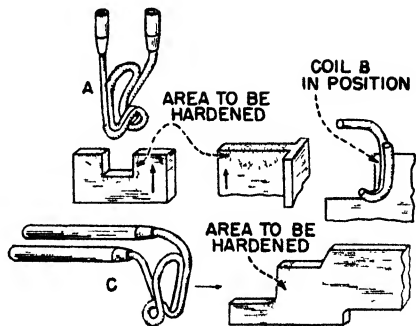
A special problem frequently encountered is the heating of the inside of a hole. Close coupling is of even greater importance than in outside heating. For large holes a regular coil may be used, but for small holes considerable difficulty arises. The coil must be water cooled, but fre-
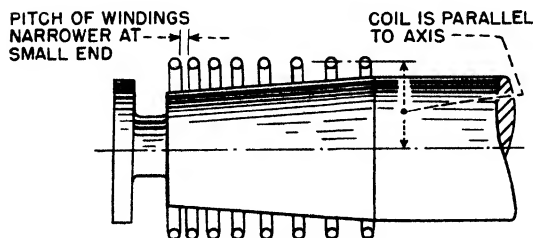
FIG. 249.   Coil shapes.[98b]

FIG. 250.   Coil shapes
(pancake coils).[98b]
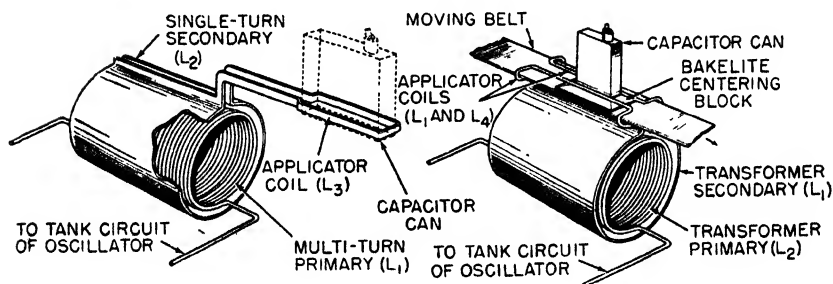
FIG. 251.   Coil shapes for condenser cans.[98e]

quently there is not space to place in the hole a large enough cross section to allow sufficient cooling water to pass. Roberds [98c,d] suggests combined induction and direct-heat resistance heating (Fig. 252); a hollow concentrical electrode, E_1, is placed in the bore, and the workpiece itself serves as return lead. Plates B and E are, for this purpose, pressed tightly to the ends of the electrode.

To heat an open notch M, N, which does not offer a closed loop, the loop may be closed artificially by a high conductor material, which will absorb some power, but because of the lower resistivity only a small portion. In the loop thus formed, a coil, I, may be placed (Fig. 253).

Usually if a charge is placed in a coil all sides heat fairly uniformly. If only part of the surface is to be heated, copper shields (Fig. 254) can

    [98] (a) G. Babat, *Heat Treating Forging*, **27**, 39, 89, 137, 192 (1941).   (b) F. W. Curtis, *Am. Machinist*, **87**, 83, 94 (1943).   (c) W. M. Roberds, *Iron Age*, **154**, 50 (1944). (d) W. M. Roberds, *Electronic Ind.*, **3**, 80 (1944).   (e) J. P. Taylor, *Electronics*, **17**, 114 (1944).   (f) J. T. Vaughn and J. W. Williamson, *Elec. Eng.*, **64**, 587 (1945).   (g) J. W. Cable, *Aviation*, (Aug. 1942).

prevent heating at undesired places. The copper blocks, C, prevent the ends of the workpiece, W, from absorbing heat. A relatively small
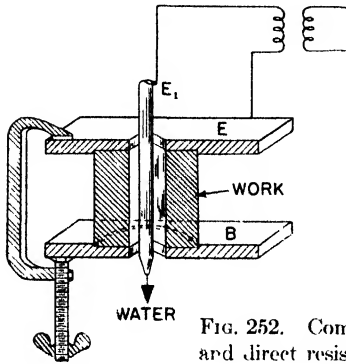
FIG. 252. Combined induction and direct resistance heating.[98d]
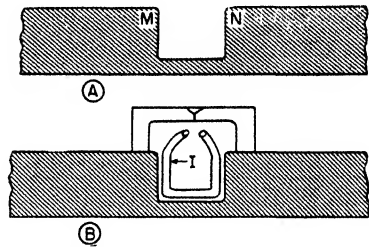
FIG. 253. Heating open notches.[98d]

amount of heat is generated in the copper. The parts, C, extending over the entire thickness of W may cool also those parts of the faces A and B which join C. If this is undesirable C can be made somewhat shorter than the thickness of W.

"Flux concentration" may be employed to concentrate heat generation (Fig. 255). Placed between the coil and the charge, the "concentrator" has an annular wedge protruding at the level at which heat concentration in the charge is desired. Instead of
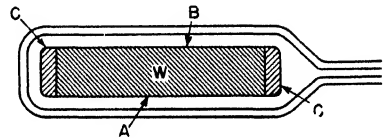
FIG. 254. Copper shield for localized heating.[98c]
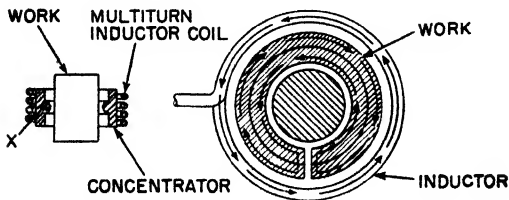
FIG. 255. Flux concentration.[98d]

copper tubing for the coils solid metal may be used, with an attached cooling section (Fig. 256).

COILS FOR CONTINUOUS HEATING

Where simple shapes, such as rods—round or rectangular—or pipes, must be heated over a considerable length, it is often advantageous to provide a coil of limited length and to change the mutual position of coil

and workpiece, by moving one or both.   In determining the length of the coils, two factors should be considered: the time of heating, and the local energy density.   Consequently, the depth of heating is also influenced. If no considerations of this kind enter, the problem of efficiency arises. The longer the coil, the better the electric efficiency; but since a long coil means greater heat losses, an optimum length should be determined.
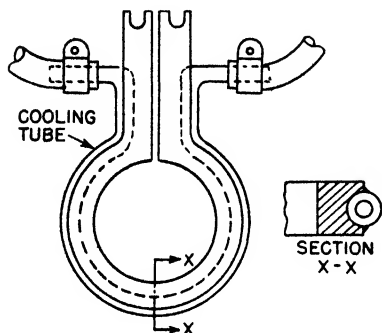
FIG. 256. Coil with cooling attachment.[98b]
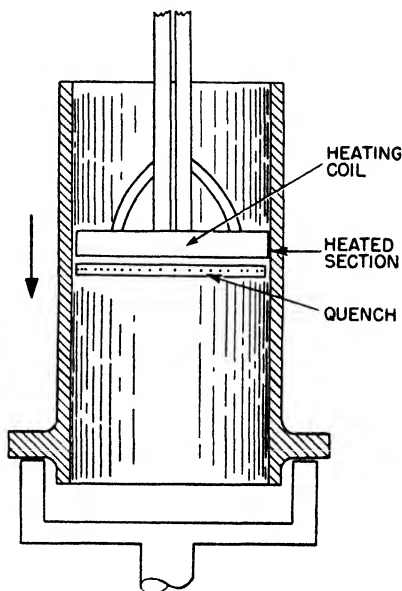
FIG. 257. Internally heated cylinder.[98g]

Figure 257 shows a schematic cross section through a cylinder head, with a short internal heating coil which successively heats different parts of the inside surface of the cylinder.   Frequently the piece, or more rarely the coil, is rotated during the heating process, as every coil has slight unsymmetry because of the current connections.[99]

SINGLE-TURN COILS

When high power densities are needed, single-turn coils have found useful application.   The efficiency for comparable conditions is less for a single-turn coil, compared with a coil of several turns.[100]   For high power rating, efficiency must be sacrificed, or the voltage would become unmanageably high.   If, for a single turn, no tubes can be used, the coil can sometimes be cooled by spraying water against it (Roberds' Fig. 11[99]).

[99] H. E. Somes, *Iron Steel Engr.*, **18**, 39 (1941).
[100] W. M. Roberds, *Electronic Ind.*, **3**, 80 (1944).

(e) The Problem of Tuning and Coupling

Induction heating has been described above as being based on the transformer principle. Like every transformer, the "air transformer," which transmits the energy from the "primary" inductor coil to the "secondary" load, can function properly only if the primary and secondary are correctly coupled. This coupling requirement necessitates a small distance between inductor coil and load.

For many applications requiring no special precautions, a number of turns placed close to the load will be satisfactory. Such applications include all through heating and such surface heating as extends over sufficient length, e. g., a rod or cylinder to be heated over many inches of length to a relatively small depth. But if the length of the heated zone is limited or if only a shallow depth is to be heated, conditions require single turn coils. If the length of the heated zone is small, there is no place to put several turns with dimensions sufficient for proper cooling.

For very shallow heating, high power-input rates and high frequencies are required. Both make necessary high voltage, which can be reduced only by reducing the number of turns. This kind of application necessitates a further link in the output circuit between the terminals of the high-frequency power supply and the inductor coil. This additional link is usually a transformer, the primary of which is connected to the high-frequency power supply, or may be part of the latter's tuning inductance; the secondary is connected to the single turn inductor coil.

Roberds [100] describes a number of such "transformers." In Figure 251, the inductor coil surrounding the workpiece is connected to a single-turn secondary of a transformer, with the multiturn primary located inside. Primary and secondary should be spaced as closely together as the voltage will permit. To allow narrower spacing, primary and secondary together may be placed in a container and the latter filled with oil or gas to improve the insulation. Roberds recommends a ratio of length to diameter of 1.5, and states that with this ratio the secondary has an inductance (measured in microhenry) of approximately 0.01 of its diameter.

In another type of transformer (Fig. 258), two windings are placed in the form of two parallel helices, the primary consisting of tubing, the secondary of copper strip. The turns of the secondary are all connected in parallel, thus forming one loop. There is an appreciable capacity between primary and secondary in this type of transformer.

Finally, for small output, one can use a coaxial line consisting of a tube conductor into which, centrally, a rod is placed as second conductor. At one end tubing and rod are connected to the power supply, at the

other to the loop.   The length of the arrangement must be one-fourth of the wavelength.

For tuning, condensers are usually placed in the generator circuit. Occasionally separate condensers are connected close to the inductor coil, particularly for very high frequencies.
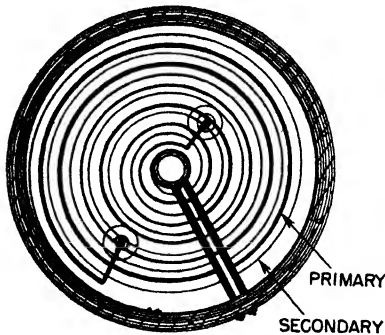
FIG. 258.   Coaxial transformer.

(f) Special Features

QUENCHING

As previously discussed (pages 265–267), modern HFI heating permits under certain circumstances "self-hardening" without applying a quenching medium.   Ordinarily, however, quenching by a coolant is necessary.   The compact arrangement of induction heating permits quenching immediately upon completion of the heating.   One design uses openings in the inductor coil to carry the quenching water and squirt it against the workpiece.   Figure 259 shows a single turn inductor block, hollow and provided with water inlet and outlet.   As soon as the heating is completed, water is pressed through the inductor and through the jets, out onto the workpiece.   In another method of cooling, a separate quenching ring is independent of the inductor, and a third method consists of spraying the quench between the turns of the coil.
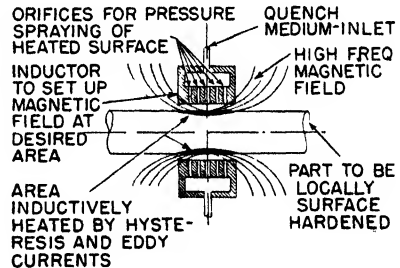
FIG. 259.   Quenching means.

CONTROL

Since the very short times involved in induction heating render temperature measurements during heating impractical, a control of the heating cycle based on temperature measurements is not feasible.   Rather, a control based on time is required.   This becomes particularly important for operations where only part heating is desired.   Correct times are established by trial and error, treating individual pieces and testing the product for desired properties (hardness, anneal, etc.).   Times are then maintained automatically by switching the power on and off, sometimes to within 0.1 sec accuracy.   Osborn [93] has shown that the delay between

switching off the power and turning on the coolant are of as much importance as the heating time. Delay in supplying the coolant leaves more time for heat equalization in the piece. The time control may also include movement of the piece, particularly in continuous operations.

AUTOMATIC HANDLING

The necessity for maintaining accurately a small distance between coil and workpiece makes continuous operation in induction heating difficult except for a few simple cases. A further complication arises from the necessity of avoiding metal parts in the conveyor mechanism, because metal would be heated by the stray fields. On the other hand, the fact that the heat source (inductor coil) is cold, helps.

There are two general methods possible: keep the inductor coil in a fixed position and move the load, or keep the load fixed and move the coil. As an example of the latter method, Somes [101] describes a machine for heating and quenching entirely mechanically hollow bodies (tubes, hubs, etc.), the operator's only function being to place new workpieces in the fixture. Figure 260 conveys an idea of the complexity of the control mechanism, consisting of cam-operated switches.

The first method is exemplified by the arrangement in Figure 251 (page 270). Another application of this method comprises a turntable on the perimeter of which pieces are prepared. The table is lifted, thus placing a piece in the inductor coil. At the end of the processing time (which may include heating only or heating and quenching), the table is lowered, turned one step, and lifted again. Depending on the speed of heating and the difficulty of fastening the work to the turntable, one or two operators are employed to load and unload the turntable.

PROTECTIVE ATMOSPHERE

The lack of enclosures which could be made gas-tight makes the application of protective atmospheres in induction heating appliances difficult. Fortunately the short duration of heating cycles counteracts this difficulty. First, since the short times result in less oxidation, there is less need for the application of special atmospheres. Secondly, open flow of gas is economically acceptable because of the short heating times. In some instances a gas jet which ejects gas all around the workpiece is provided. The jet can be linked to the power switch or to the timing device, so that gas flow occurs only when the piece is being heated. In one specific plant hundreds of kilowatts are used for brazing in hydrogen by induction heating.

[101] H. E. Somes, *Trans. Electrochem. Soc.*, **79**, 45 (1941).
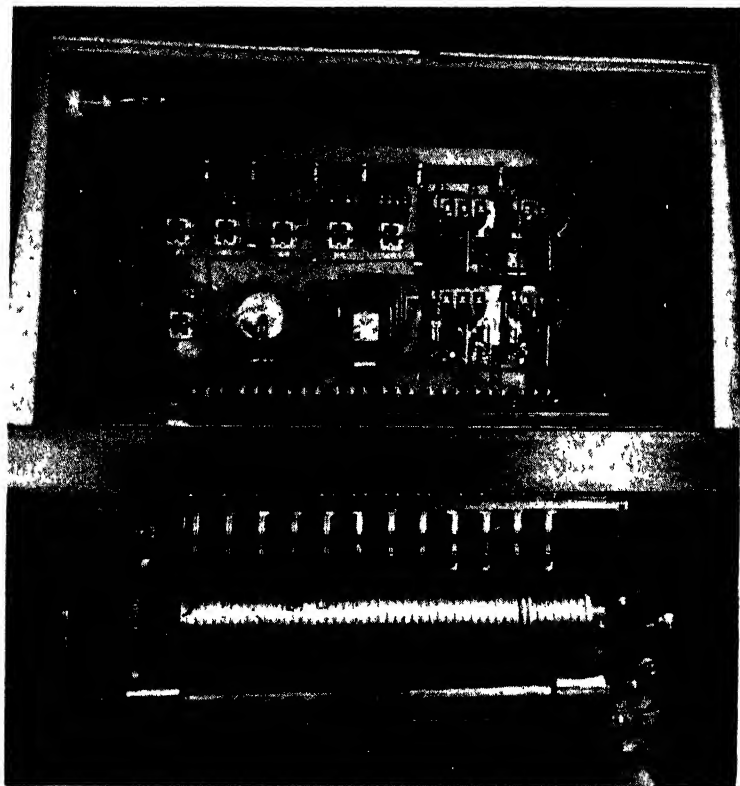
Fig. 260.   Cam-operated switches.

IV. HIGH-FREQUENCY CAPACITANCE (HFC)
OR DIELECTRIC HEATING

Equipment for high-frequency capacitance heating is very simple. It consists of a high-frequency generator, almost always of the tube type (page 219) and enclosed in a cabinet provided with the necessary controls From the terminals of the power supply, short leads (page 288) provide the connection to electrodes (page 285).   Usually application of heat is controlled by the input rate and time, but occasionally temperatures are measured (page 290).   Frequencies vary from one megacycle to several hundred, the range most frequently used being from 10 to 30.

A.   APPLICATIONS

Dielectric heating is limited to nonconducting materials with a high dielectric constant ("inductive capacity").   Because this method of heating is relatively new, its scope and usefulness increase constantly.   At

present perhaps the two greatest applications are in the working of plastics and wood.

Plastics. The main use here is the heating of pre-forms, which are blocks of raw plastic, roughly the shape of the finished part. Pre-forms were previously heated in the press; the platens comprise steampipes which supply heat to be transferred to the pre-form. To increase the output of the presses separate ovens were used; however, the uniformity requirements are so high that extremely slow heating, in ovens, was necessary, resulting in a limited output.

HFC heating replaces ovens, and heats the pre-forms far more uniformly and in a fraction of the time required in ovens.[102] Occasionally HFC heating is used to prepare the raw material in powder form. Powder is, however, not easily heated with sufficient uniformity because the powder, when placed on an electrode, may take an odd shape (Fig. 261), thus offering a nonuniform resistance to

Fig. 261. Shape of powder pile.

the electric field (see page 285). If the powder is in a container, the walls of the latter deform the field and cause new difficulties, which can be lessened but not eliminated by appropriate choice of the container.

Wood. There are three main applications for HFC heating in the processing of wood: drying, gluing, and, more rarely, bending.

Its use in drying is important because in conventional drying procedures [103] the danger of forming a relatively dense crust (which prevents the escape of the moisture from the center) can be overcome only by very slow drying. In HFC heating the center gets hottest and the formation of a hard crust before the center is dry is eliminated. However, the high cost of equipment as well as of electric power makes dielectric drying economically acceptable only for high quality products.

Gluing by so-called "thermosetting" glues involves the application of the glue and the exposure of the whole construction—wood and glue—to dielectric heat and pressure at the same time. By appropriate choice of the electric properties of the glue in relation to those of the wood, heat generation can be concentrated in the glue.[104]

In medicine, sterilization of nonmetallic objects should be mentioned; diathermy is a dielectric heating.

[102] J. P. Taylor, *Electronics*, 16, 102 (1943). P. D. Zottu, *Product Eng.*, 14, 40 (Jan., 1943). L. C. Brumleve, *Plastics*, 2, 79, 353 (March, 1945).

[103] G. F. Russell and J. W. Mann, *Trans. Am. Soc. Mech. Engrs.*, 66, 563 (1944).

[104] J. P. Taylor, *Trans. Am. Soc. Mech. Engrs.*, 65, 201 (1943); *Electronics*, 16, 102 (Sept., 1943); 17, 96, 108, 102 (Jan., Mar., April, 1944). R. A. Bierwirth and C. N. Hoyler, *Proc. Inst. Radio Engrs.*, 31, 529 (1943). G. H. Brown, *ibid.*, 31, 537 (1943).

In the manufacture of textiles, HFC heating has found a number of useful applications.   Rayon cakes can be dried "from the inside out" more rapidly and more uniformly by dielectric heating than by external application of heat.   Twist setting of thread is accomplished in continuous operation with HFC heating, as is the drying of cotton goods.

A relatively new application of wide promise is that of dehydrating food, which can be effected with dielectric heat at lower temperatures than with other methods of heating.

In the manufacture of glass, two important applications are the "gluing" of laminated glass and the sealing of metal in glass.   Laminated glass consists of alternating layers of glass and plastic.   To manufacture a solid body, the plastic must be heated to its softening point.   The sealing-in of metallic parts into a glass body was made difficult by the simultaneous heating of metal and glass.   Now the glass alone may be heated dielectrically to the softening point.

In the vulcanizing of rubber, dielectric heat plays an increasingly important role.   Finally, a number of miscellaneous applications may be listed: drying of explosives; heating of lipstick for pouring into containers; drying of foundry cores; sealing; "sewing" rubber and other materials by heating seams made of thermosetting plastics.
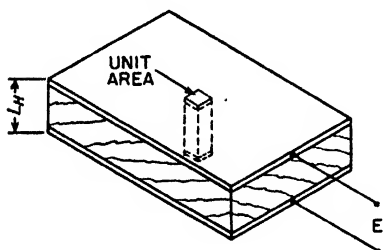
FIG. 262.   Schematic arrangement of electrodes.

B.   ELECTRICAL PROBLEMS

1. Principles

The power across a condenser of unit area, located in the center of a large condenser (Fig. 262) may be expressed [105] by:

$$W = E^2 \cos \varphi / \sqrt{R^2 + X_E^2} \tag{68}$$

where E = voltage across the electrode, R = resistance, and X_E = inductive load (capacitance).   It is important to remember the assumption that the small condenser be located in the center of a large condenser; the formula applies only if the electric field is perpendicular to the condenser surface.

In Equation (68), R is not convenient to handle.   It is customary to replace R by X and $\cos \varphi$:

$$X_E / \sqrt{R^2 + X_E^2} = \sin \varphi = \sqrt{1 - \cos^2 \varphi} \tag{69}$$

[105] R. A. Bierwirth and C. N. Hoyler, *Proc. Inst. Radio Engrs.*, **31**, 529 (1943).

Moreover;

$$X_E = 1/2\pi fC \tag{70}$$

and C, because it is referred to unit area, is (in farad per sq in.):

$$C = 2.25\partial/L_H \times 10^{-13} \tag{71}$$

where L_H is the thickness of the material, and ∂ the dielectric constant. By combining Equations (68) and (71) and by introducing

$$E_g = E/L_H \tag{72}$$

for the voltage gradient or field strength, the formula for the power per unit volume, W_v, can be written as in Equation 73 (W per cu in.):

$$W_v = 1.415 \times 10^{-12} \times f\partial(E_g)^2\sqrt{1 - \cos^2\varphi}\,\cos\varphi \tag{73}$$

Since $\cos\varphi$ is usually very small — of the order of magnitude of $0.01 \rightarrow 0.1$, $\sqrt{1 - \cos^2\varphi} \sim 1$ and Equation (73) may be simplified to:

$$W_v = 1.415 \times 10^{-12} \times f\partial(E_g)^2\cos\varphi \tag{73a}$$

Exceptions, calling for the use of Equation (73) instead of the approximate solution (73a), are, for example, the heating of electrolytic solutions and sponge rubber.[106]

A table of dielectric constants and power factors of some materials is shown in the appendix. The figures are, however, to be considered as only indicative, because neither values are constant, but change with frequency and/or temperature. The voltage mentioned in Equation (73) and (73a) is that between the electrodes. In order to obtain full usefulness from the power supply, the circuit must be in resonance. The capacity must be compensated by an inductance. This procedure is called
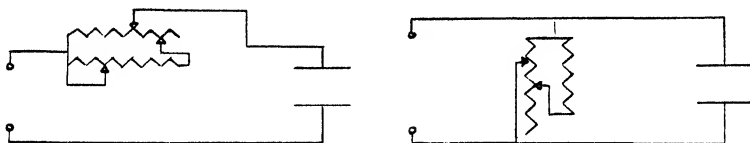
Fig. 263.   Tuning circuits.

"tuning" and can be accomplished by either a parallel (a) or a series (b) inductance (Fig. 263). The change in capacitance necessitates a variable reactor as inductance. In some instances automatic tuning is provided; the reactor changes its position until maximum power is obtained.

[106] Paul D. Zottu, in "Symposium on Dielectric Heating," AIEE Convention, New York, 1945.

2. Voltage and Frequency

Equation (73) obviously shows that the power changes with the square of the voltage and in direct proportion to the frequency. This statement is, however, misleading because power factor and dielectric constant usually increase with frequency. Therefore an increase of frequency causes a more than proportional growth of the power. The relationship between voltage and frequency is important: by increasing the frequency the required voltage can be reduced. Inasmuch as dielectric constant and power factor are inherent to the material to be heated, the only selections to be made are those of voltage and frequency.

Tubes for very high frequencies are hard to make, particularly for a great power input. From Equations (73) and (73a) it is apparent that, for a given frequency and physical properties, only an increase in voltage will increase the rate of power generation. Increase of voltage is limited by two factors: the dielectric strength of the material and the safety of the operator. In connection with the latter it is important to know that even very high voltages are not lethal at high frequencies. Because of the skin effect, the current does not penetrate into blood vessels, nerves, and the inside of the body, but remains on the skin. Yet painful burns may be suffered, and therefore protection against inadvertent touching of high-voltage parts is usually provided.

The main limitation for increase of the voltage is the dielectric strength of the heated material. At a given voltage the conductivity of any material suddenly increases rapidly and a "flashover" occurs. Such flashovers are of course detrimental to the material and also to the elements of the circuit; they form what amounts to a short between the electrodes. The critical voltage at which the flashover occurs decreases with increasing thickness of the material; small thicknesses suffer a flashover more easily than large ones. Therefore thin sections must be heated with lower voltages; and this in turn may limit the rate of power input, if the frequency cannot be increased. This applies not only to the total rate of input, but also to the rate per unit volume. The relative importance of heat losses is also larger in thin pieces than in thick ones, and therefore there is a limitation to heating of thin sections by HFC heating.

Increase of the voltage may also lead to the point of corona formation. From all these considerations a maximum over-all voltage of 15,000 or at the highest 20,000 v between the electrodes may be applied, but usually it is desirable not to exceed 10,000 to 12,000 v. The permissible voltage gradient depends somewhat on the material; a gradient of 2,000 to 4000 v per in. may be quoted as typical, which would incur a lower limit of thickness that can be treated of 0.05 to 0.1 in. Generally such thicknesses would be considered too low.

Equations (73) and (73a) apply where only one material is used between the electrodes. If the electrodes are not in contact with the charge, the air between electrode and charge is considered as in series with the charge. Before discussing this case, the voltage gradient will be considered.

3. Voltage Gradient — The Electric Field

In the previous section the most common arrangement was considered—that of two parallel electrodes between which a charge of constant thickness was placed. The influence of shape and uneven
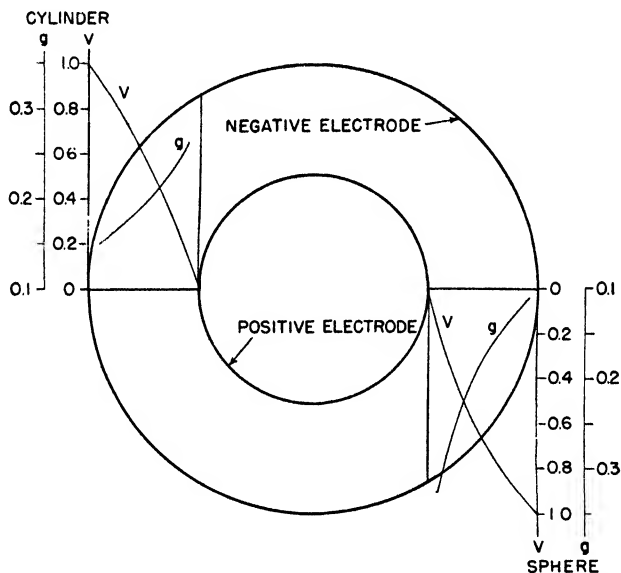
Fig. 264.   Voltage drop (V) and voltage gradient (g) in cylinder and in sphere.

thickness—important because, should the field lines not be parallel (that is, the field not uniform), the heat generation is not uniform—will now be examined. The heating in any one element of the body is proportional to the square of the voltage gradient, and if the gradient is nonconstant, heating is likely to be nonuniform. A partially unavoidable irregularity of the field is caused by the end effect. The air surrounding the piece to be heated offers paths for the electric field lines, and the field near the end of the charge is distorted.

In Figure 264, representing a hollow cylinder to which two electrodes are applied, the voltage drop is shown as a curve and finally the gradient (v per in.) as function of the position. On the right bottom part of the

figure two similar curves are plotted, which apply for the case in which the circles represent a hollow sphere rather than a cylinder. It is noteworthy that the voltage drop between two electrodes follows exactly the same law as the temperature drop in a body if certain parts of its surface (those covered by the electrodes) are exposed to a given temperature difference. The pattern of field distribution is independent of the actual value of the potential applied, and, provided the material is homogeneous,

SECTION A

NUMBERS DENOTE PERCENTAGES OF TOTAL VOLTAGE

SECTION B
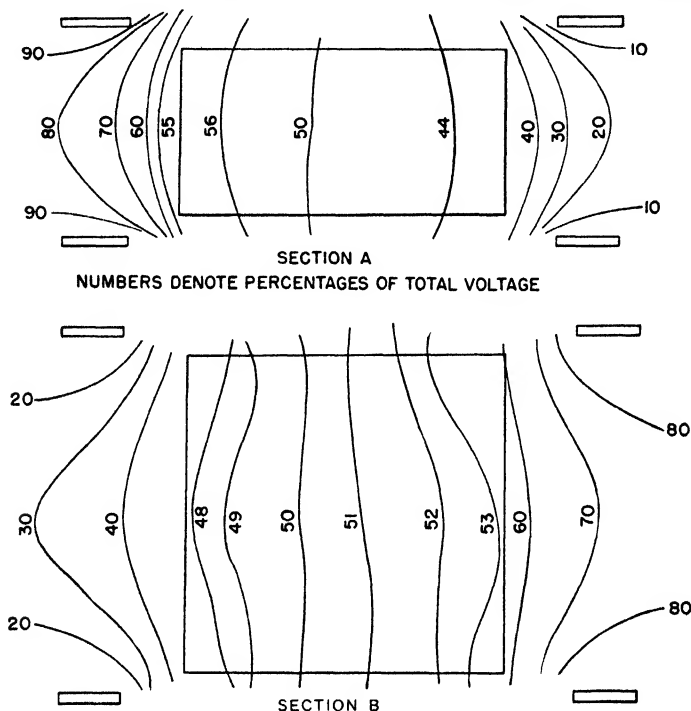
FIG. 265. Voltage distribution lines. (Courtesy
Illinois Tool Works, Electronic Department.)

independent of the physical constants of the material. By scanning the voltage distribution over a body of any shape or size, the field distribution and therewith the uniformity of HFC heat application to the body can be found. This technique necessitates care that the voltmeter resistance does not influence the voltage distribution.

Figure 265 shows two such field distribution charts. Heating, as explained above, is proportional to the voltage gradient. Note that the voltage lines in the center are reasonably parallel. In Figure 265A the spacing is closer in the upper part (56 to 50) than in the lower (50 to 44); but in Figure 265B the lines are approximately equidistant. The crowding at the edges is clearly to be seen.

4. Two Materials in Series or in Parallel

Frequently it happens that two materials are placed in series between two electrodes (Fig. 266). The total voltage, E, between the two electrodes is consumed in the two materials, according to their dielectric constants, ∂_A and ∂_B, and their thicknesses, L_A and L_B:

$$E_A/E_B = L_A\partial_B/L_B\partial_A \tag{74}$$

This relationship is important because the electrodes frequently do not touch the charge. Then the air must be considered a material in series with the charge, and the voltage across the electrodes must be increased.

Fig. 266. HFC heating —two materials in parallel (left) and in series (right).
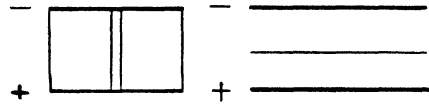
To facilitate calculation of the over-all voltage, with air gaps between electrodes and charge, a chart has been prepared by Mittelmann.[107] It applies for a power factor equal to unity, which, of course, does not occur in practice. A scale [108] is added which allows correction for the power factor (Fig. 267). In considering the diagram it should be kept in mind that the impedance of the load is governed by the ohmic resistance alone; in the range of radio frequencies the capacitance has no appreciable influence on the magnitude of the impedance. Though first surprising, this relationship may be understood from the following remarks. The losses of the condenser can be considered as originating in a resistance parallel to the capacitance. If the power factor in a specific case is 0.1, the resistance is approximately one-tenth of the capacitance. The over-all impedance can be roughly calculated for two parallel resistors (Vol. I, page 60). If one resistor (resistance) is 1/100 of the other (capacitance), then the over-all resistance or impedance is governed by the smaller item, namely, the resistance.

Example for the Use of the Chart. Power absorption desired, 250w; load impedance, 160 ohm; power factor, 0.045; electrode area, 80 sq in., and wavelength, 12 m ($f = 25$ megacycles); with a spacing, D, between electrodes and charge of 0.7 cm for 1400 v across the electrodes, with $D = 1$ cm spacing for 2000 v, etc.

Draw (arrow 2) a line at a 45-degree angle from point "250" on the power absorption scale, until intersection with horizontal "160-ohm impedance" line. Determine length of "p" from power factor scale for desired power factor and mark it on "160 impedance line." Extend a vertical arrow (3) until intersection with 80 sq in. inclined line, thence (arrow 4) to 12 m wavelength.

[107] E. Mittelmann, in *Electronics for Engineers*. McGraw-Hill, New York, 1945.
[108] E. Mittelmann, *personal communication*.

From intersection draw (arrow 5) a line under a 45-degree angle. From the intersections of the latter with the lines of the network, the values (0.7 cm − 1400 v, etc.) are determined.
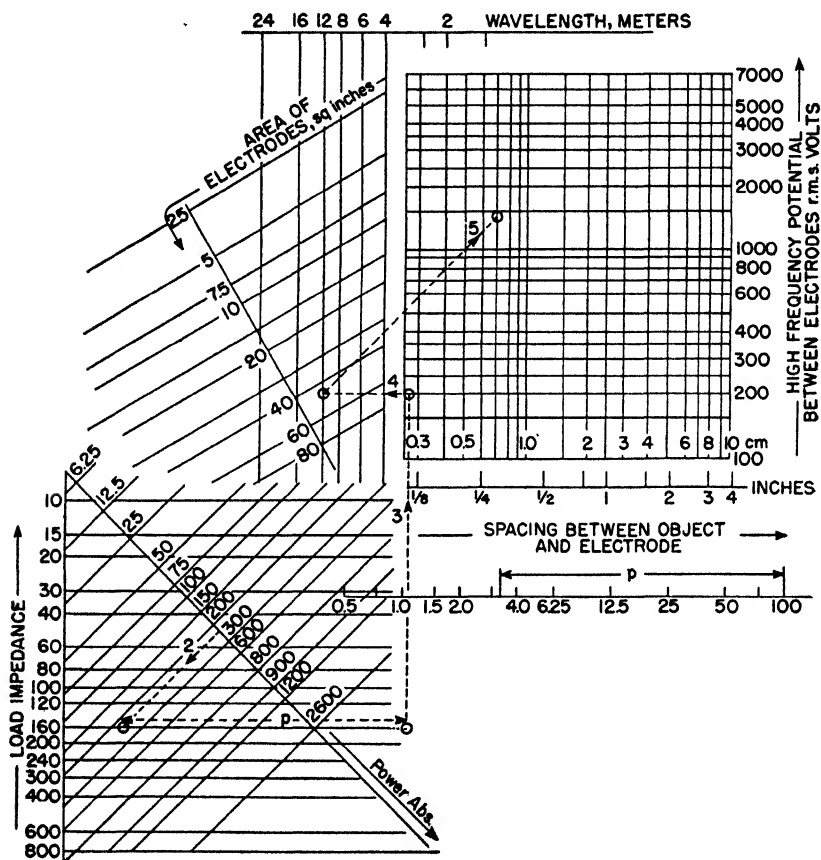
FIG. 267.   Chart for relationship of air gap, voltage, and frequency.

Where two materials are in parallel, the field in each material will be disturbed by that in the adjacent material.   Conditions are similar to those described in Volume I (page 51) for thermal short circuits.   In first approximation the mutual influence may be neglected and power may be assumed to be generated in each material separately and according to Equation (73) or (73a).   Therefore if one material has a higher dielectric constant and/or power factor, the heat generation in this material will be stronger than that in the other material.

A practical application of this phenomenon is the gluing of wood with certain types of glue which have a higher ∂ and cos φ than wood, and

which heat, if placed between the electrodes as in Figure 266 (right side), more rapidly than the wood.

C. DESIGN

1. Electrode Shape and Design

Various forms and shapes of electrodes are used for different applications, the problem of design being to shape an electrode which will result in a uniform field in the body, if uniform heating is desired. A simple example is shown in Figure 268, taken from Taylor.[109] If an inclined
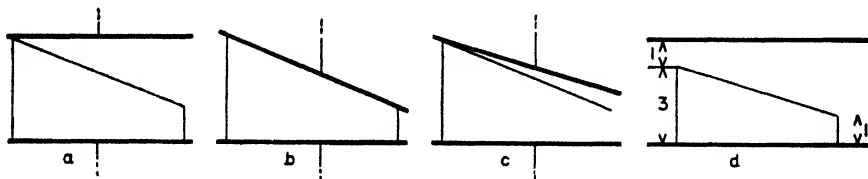
FIG. 268.   Shapes of electrodes.

pile of material (*e. g.*, wood) is to be heated, arrangement (a) cannot be used because the voltage gradient across the wood on the left side would be very much higher than on the right side, and uneven heating would result.   Arrangement (b) cannot be used because the gradient at the right side would be very much steeper.   But a design as shown in Figure 268c would result in uniform heating.   If the wood to be heated has a value of $\partial = 4$, one inch of air has as much resistance as four inches of wood and the spacing can be calculated accordingly.   To give the same voltage at the thin end as at the thick, the air space should be:

$$\frac{\text{thickness thick end} - \text{thickness thin end}}{4}$$

It would also be possible to place between the electrode and the material a spacer or filler of a material similar to the one to be heated.   This filler will also receive heat, thus lower the efficiency of the process; however, the uniformity will be increased as compared to that with arrangement (a). Or an air space may be inserted on both sides, that is, on the thick and the thin ends (Fig. 268d).

In Figure 268a, the gradients at the left and the right ends are $E/3$ and $E/9$, respectively; they are in the ratio of 1 to 3.   (The value, $E/9$, is found by determining which part of the total voltage, E, is absorbed in the wood, namely, $E/9$; since the thickness is 1 in., the gradient numerically equals voltage.)   By inserting an air gap of one inch, the

[109] J. P. Taylor, *Trans. Am. Soc. Mech. Engrs.*, **65**, 201 (1943).

gradients drop to $E/7$ and $E/13$, respectively; their ratio is less than 1 to 2. However, only a smaller part of the voltage is useful. Voltage has been sacrificed for uniformity. Whether electrode or charge should overhang is difficult to decide. Generally, electrodes slightly larger than the charge are beneficial.

SOURCE OF HIGH-FREQUENCY POTENTIAL

DISTRIBUTION OF DIELECTRIC FIELD BETWEEN FLAT ELECTRODES

DISTRIBUTION OF DIELECTRIC FIELD BETWEEN FINGER TYPE ELECTRODES
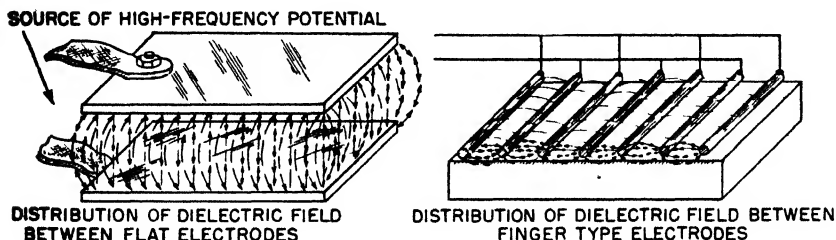
FIG. 269.   Heating by stray field.[110]

The entire field may be passed through the charge, or electrodes may be placed above the charge. A stray field will penetrate into the charge and cause at least surface heating. Figure 269 [110] indicates arrangement and field distribution. This method, although not efficient, offers a means of dielectric surface heating. Another example of stray field heating is shown in Figure 270, where two concentric electrodes are placed over a flat workpiece, causing a stray field to enter and heat the charge.

WORK
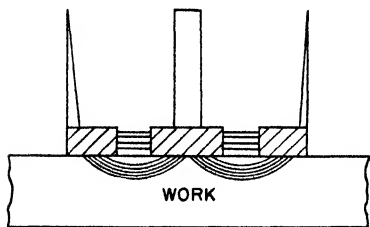
FIG. 270.   Electrodes for stray field heating.

Where the field is necessarily irregular, it has been found helpful to use a simply shaped pair of electrodes and to rotate the charge in the space between the electrodes. This method deserves attention, because shaping the electrodes to fit irregular contours is not easy. The field will be strongest wherever the two electrodes are closest. One electrode usually may be grounded, which is desirable when the electrodes are built into a press or machine.

2. Long Electrodes

So far it has been assumed that the electrodes have the same potential at all points. However, it is not always sufficient to supply the current at one point only. If voltage is supplied at one end of long electrodes, as occurs in wood-gluing presses, uneven voltage distribution

[110] J. W. Cable, in *Induction Heating*. American Society for Metals, Cleveland, 1946, p. 101.

occurs. "Long," in this connection, means approaching or surpassing $\frac{1}{4}$ wavelength, where the wavelength (ft) is expressed by: [111]

$$\lambda = 984/(f\sqrt{\partial}) \tag{75}$$

where ∂ is the dielectric constant. The voltage distribution can be expressed by the ratio of highest to lowest voltage, E_{max} and E_{min}, respec-
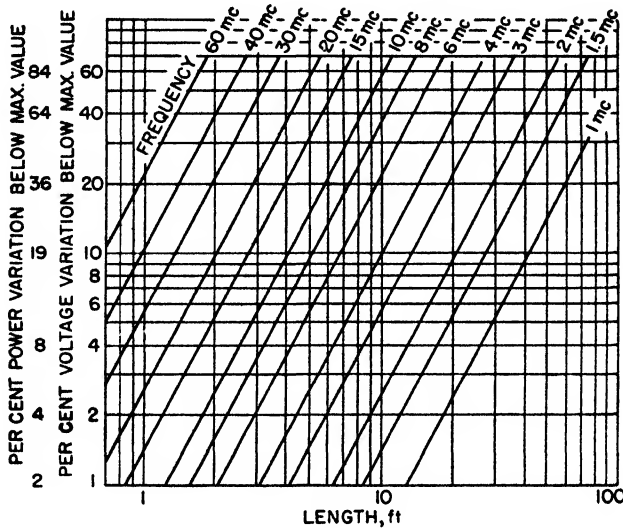
Fig. 271. Alignment chart for Equation (75).[111]

tively. If the length of the electrode, with connections on one side, is L_E and if $\cos^{-1}$ is expressed in degrees, then:

$$\cos^{-1}(E_{min}/E_{max}) = 2.74/(L_E f\sqrt{\partial}) \tag{76}$$

This equation is represented in the alignment chart (Fig. 271) for a value [112] of $\partial = 3.2$, which is reasonable for spruce wood. If the chart is to be applied to materials with a different ∂ value, change the f scale in proportion to the square root of ∂. For example, if the material has a value of $\partial = 0.8$, then $\sqrt{3.2/0.8} = 2$. The 10-megacycle line would hold for 20 megacycles, etc.

Such voltage differences are inconvenient. It was stated that the circuit has to be tuned to resonance. Since, with a somewhat undefined capacitance this is not possible, tuning inductances are placed across the plates (Fig. 272). Such inductances are, mechanically, copper tubes

[111] R. A. Bierwirth and C. N. Hoyler, *Proc. Inst. Radio Engrs.*, **31**, 529 (1943).
[112] R. A. Bierwirth, *personal communication*.

which may, by means of a bridge piece, be cut to greater or smaller "electric length" (Fig. 273).[113]   The beneficial effect of tuning inductances may be seen from Figure 274, which shows the voltage in per cent of the maximum for a 13-ft long heater (press) with and without tuning inductances.   The frequency is 45 megacycles.

TUNING INDUCTANCES CONNECTED ACROSS PRESS PLATES

VOLTAGE DISTRIBUTION ALONG PRESS

FIG. 272.   Tuning inductances.[111]

The required size of the tuning inductances (microhenry) is shown by Bierwirth and Hoyler [111] to be:

$$L = (N \times 10^6)/(4\pi^2 f^2 C) \quad (77)$$

where C is the capacitance of the electrodes in micromicrofarad and N the number of evenly spaced inductances.
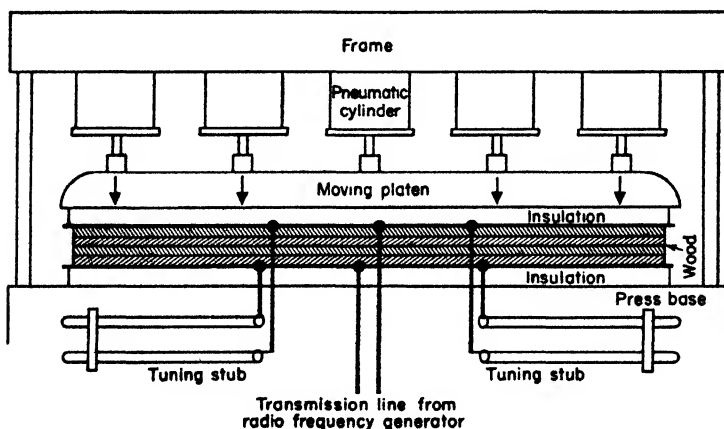
FIG. 273.   Tuning inductances.[113]

3. Auxiliary Equipment

(a) Connections and Leads

The connections from the power supply to the electrodes should be as short as possible.   But even with greatest care in design they will cause radiation losses and, because of the very high frequencies, ohmic losses. Though the high voltage results in small current, the flow is in an extremely thin layer.   To minimize radiation losses, the leads are made, as far as possible, concentric, and connections from the leads to the elec-

[113] J. P. Taylor, *Electronics*, 17, 114 (1944).

trodes are kept short (Fig. 275). Since electric fields are strongest around corners and wires of small diameter, sharp bends in the leads are avoided and tubes are used instead of wires.
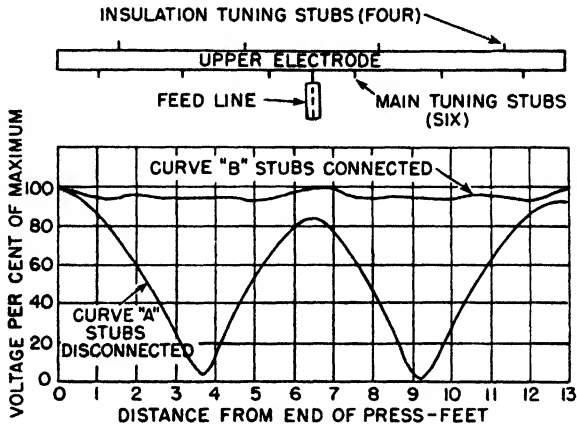
FIG. 274. Influence of tuning stubs.[111]
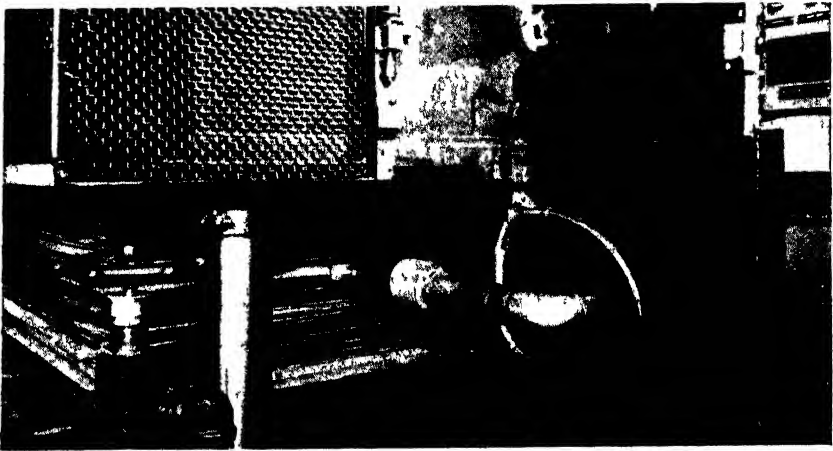
FIG. 275. End view of concentric conductor. (Courtesy *The Girdler Corporation.*)

Frequently it is desirable to measure the power factor or the "Q value" of an element of the circuit or of the charge. This can conveniently be done by use of a "Q Meter." Q is the ratio of the inductive resistance to the ohmic resistance of the piece, inductive resistance comprising here also the case of a capacitance. The method [114] on which the

[114] F. E. Planer, *Electronics*, **16**, 190 (1943).

Q Meter is based, can briefly be described as resonating a circuit comprising the unknown element and a calibrated nonleaking condenser.

(b) Measuring Devices

On the input side, normal a-c instruments are used to indicate proper tuning, and though usually no measurements are made on the high-frequency side, voltage across the electrodes may be measured by a circuit as shown in Figure 276. However, readings on the a-c milliammeter will depend on the frequency, necessitating recalibration for each frequency.
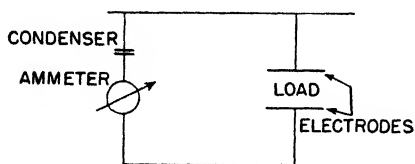
FIG. 276. Measuring circuit for voltage.

Temperature measurements are quite difficult to make, because the thermocouple wires may pick up a high potential and either damage the instrument or cause erroneous readings. Sometimes it is possible to embed a thermocouple in the charge, and connect it to the instrument only after switching off the power. By taking several readings at specified times and extrapolating the time-temperature curve to "zero time," i. e., the moment of disconnecting the power, the temperature may be established. Bierwirth and Hoyler [111] suggest various means, for example, placing the interwoven thermocouple wires in a choke coil. With 10 to 15 megacycles, 100 turns on a $\frac{7}{8}$-in. Bakelite tube were considered satisfactory for the choke coil.

D. THERMAL QUESTIONS

1. Survey of Problem

High-frequency capacitance heating (HFC) presents the same kind of thermal problems as do direct-heat resistance furnaces (page 194). Questions of uniform generation of heat all over the body, and of non-uniformity of temperature even in the case of uniform heat generation, must be solved.

Heat is generated in each particle, as explained on pages 212–214. The heat generated serves two purposes: it raises the temperature of the particle, and it flows from this particle to neighboring ones which may be at lower temperatures, and from the surface to the surroundings consisting in part of air, and partly of the electrodes. Heat generation is not actually uniform in each particle—first, because with a uniform electrical field strength, the generation depends on the electrical properties of the

body, and second, because of irregular shapes of the body and the electrodes, the field strength is not uniform. Matters are complicated because the thermal properties governing the heat flow are in themselves also changing with temperature.
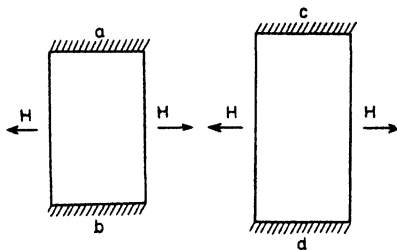
FIG. 277. Thermal principles of dielectric heating: *a*, *b*, *c*, and *d* are completely insulated.
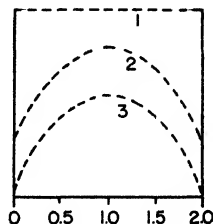
FIG. 278. Three different assumptions for heat loss in dielectric heating.

The complexity of the mathematics involved is such that so far solutions have been worked out for "one-dimensional problems" only. "One-dimensional" implies that the heat, generated at a uniform rate and uniformly in each element of the charge, flows out of the charge only through two parallel surfaces, *H*, *H*, all other surfaces, *a*, *b*, *c*, and *d*, being completely insulated with a material having no heat storage capacity (Fig. 277). A long cylinder with completely insulated parallel faces and no heat storage capacity of the insulation is also a "one-dimensional problem" in this respect.

Even in one-dimensional problems with constant thermal properties, a number of complications arise. In Figure 277, arrows *H* indicate "heat losses" occurring on faces to which energy is transferred by means of electrodes which may or may not be in physical contact with the face of the material.

Two limiting cases may be described: surfaces *H* may be thought of as being completely insulated; or, as the opposite limit, surfaces *H* may be considered as held permanently at the initial temperature (the room temperature), so that temperatures rise only in the center. Actual conditions lie between the two limits. In Figure 278 distances from the center plane are plotted as abscissas. The total thickness of the piece is 2, the distance to ½ thickness 0.5, etc. Temperatures at the end of a given time are plotted as ordinates over the room temperature as zero. Line 1 shows the condition for the limit "no heat loss," line 3 for the other limit, "surfaces held at room temperature"; line 2 indicates a practical case located between the two limits. Note that, after a given time, and assuming heat generation is at the same rate in all three cases, the tempera-

ture for line 1 is highest, and incidentally uniform throughout, whereas the temperature for line 3 is lowest. The difference in heat content between condition "line 1" and either of the two other conditions is demonstrated by the difference of average temperatures, and results of course from the heat loss to the surrounding. This heat loss is greatest where the surface is being held at room temperature.

The three curves in Figure 278 are all drawn for the same length of time elapsed after start of heating. At early times all lines are low, and as time progresses their distances from the abscissa axis increase. To obtain a more uniform distribution in the piece, insulation may be applied to the faces. Insulation will be the more effective the lower its thermal conductivity is and the lower its specific heat. Generally, the influence of insulation is greater in long heating cycles than in short heating processes, and always greater toward the end of any heating cycle than at its beginning. Great thickness of the insulation is helpful only if heating lasts for a fairly long time. However, if short-cycle operations are carried out successively, without the insulation cooling between the various loads, the insulation gradually heats up; hence, pieces to be heated during later charges will face an ambient which is at a higher temperature than that facing pieces heated during preceding charges. As in resistance furnaces, the first loads after a prolonged shutdown of the apparatus will require a longer heating time than the subsequent loads. This does not apply for uninsulated operation, where every charge loses heat evenly to the ambient, as long as the latter remains at the same temperature.
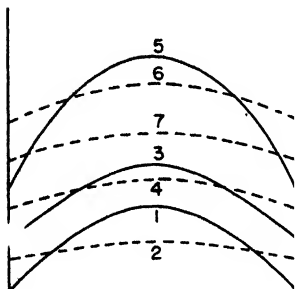
FIG. 279. Temperature–space distribution at different times.

It is well to remember that the temperature distribution under the influence of HFC heating is always of the character illustrated by line 3 in Figure 278; the lowest temperature is at the surface, the highest at the center. Two methods may be used to overcome this uneven distribution: interrupted heating and combined heating.

Interrupted heating consists simply in heating for a short period, then disconnecting the power, applying heat again, etc. During the periods of "power off" the temperature tends to become more uniform. Figure 279 represents a cross section through a slab, with temperature lines for various times indicated schematically. The solid lines (1, 3, 5) show temperature distributions at the end of "on periods" whereas the broken lines (2, 4, 6, 7) represent temperature distributions during "off" times. Lines 2, 4, and 6 may be taken as representing the distribution at the

end of an "off" period of equal length. Line 7 shows what happens if the power is then not switched on, the piece being allowed to cool still further; both surface and center drop in temperature, the differences between them decreasing at the same time. Interrupted heating does not require any special equipment, although it can be facilitated by switching on and off at regular intervals and automatically. But this method calls for a thorough analysis of the temperature rise to select properly the most advantageous time intervals for both on and off periods.

Combined heating is a combination of HFC heating (internal heat sources) with heating by conduction from outside heat sources which may or may not be electrical. It can be carried out by steam heating the electrodes, by heating them by infrared radiation, or by placing resistors in them. Figure 280 represents again a cross section of a slab. Line 2 is identical with line 3 of Figure 278 and shows the temperature distribution in the slab at a given time after start of heating under the influence of HFC heating. Line 1, holding for the same time after start of heating, indicates the temperature distribution under the influence of external heating alone. If both heating methods are applied simultaneously, the temperature distribution will be as illustrated by line 3, which represents the sum of lines 1 and 2. By proper application of such combined heating an almost uniform temperature rise may be achieved at all points of the body. To attain uniform rise, the rate of heat liberation from the external heat source must be varied with time, so that the heated piece is faced by an electrode of varying temperature.
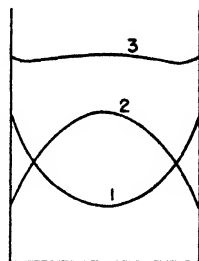
FIG. 280. Temperature distribution in combined heating.

2. Rational Analysis

(a) Completely Insulated Body

If no heat is lost from the sides, the temperature increase at all parts of the body is the same and may be expressed by:

$$W = wc(t - t_a)\theta/3413 \qquad (78)$$

where W = power (kw), w = weight of the piece (lb), c = specific heat (Btu/lb, F), t = temperature at any given time after start of heating, t_a = ambient temperature, and θ = time (hr) after start of heating.

(b) Surfaces Held at Initial Temperature

Brown [115] gives a general solution of the problem (Fig. 281). Relative temperatures, y, are plotted as ordinates: the temperatures are

[115] G. H. Brown, *Proc. Inst. Radio Engrs.*, **31**, 537 (1943).

expressed as fractions of the highest temperature reached at the center when steady state is reached:

$$y = (t - t_a)/(t_m - t_a)$$

where t = the temperature at each instant, t_m = the maximum temperature reached, t_a = the ambient temperature. The maximum temperature, t_m, may be found from Equation (79):

$$t_m = t_a + (16.7 q_v L_H/k) \qquad (79)$$

where q_v = rate of heat generation (Btu/cu in., hr of Btu/cu ft, hr), L_H = half thickness (in. or ft), and k = thermal conductivity (Btu/in., hr, F or Btu/ft, hr, F). Fractional distances, n, are plotted as abscissas; the value of n equals the ratio of the distance from the surface to the half width of the slab. Five curves are shown, holding for values of $X = 0.00432$; 0.0174; 0.0774; 0.1548; and ∞. The odd values for $X = a\theta/L_H^2$ are caused by the fact that Brown's chart was drawn for wood and not in dimensionless units.
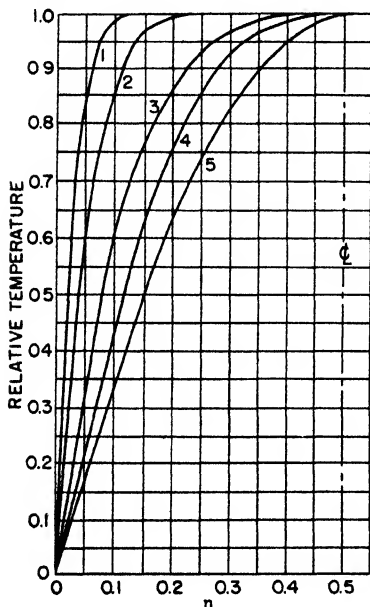
FIG. 281. Temperature functions (heating-up curves) for different values of X: curve 1, $X = 0.00432$; 2, 0.0174; 3, 0.0774; 4, 0.1548; 5, ∞.

(c) *Surface Losing Heat to the Surrounding Through a Massless Boundary Resistance*

In part (a) it was assumed that the boundary resistance, $1/h$, between the surface of the piece and the surrounding, is infinite; in part (b) it was assumed that this resistance is zero. The actual resistance lies between these two limits, studied comprehensively by Heisler [116] from whose work the following illustrations and considerations are taken.

Nomenclature.

$X = a\theta/L_H^2$ = time function
k = thermal conductivity
c = specific heat
γ = density
$m = k/L_H h$ = relative boundary resistance
h = boundary conductance
L_H = half thickness of the slab

$y_{H_n} = (t_n - t_a)k/(qL_H^2)m$ = temperature function at position n
n = relative position
t_n = temperature at position n
t_a = ambient temperature
q_v = rate of heat generation per unit volume
θ = heating time

[116] M. P. Heisler, *personal communication.*

SLAB

For values of X smaller than 0.2 it is permissible to set $my_n = X$; heat generation and heating time are correlated by:

$$q_v\theta = c\gamma(t_c - t_a) \tag{80}$$

This equation is derived as follows: by definition y_{H_n} becomes, for the center, y_{H_c}:

$$y_{H_c} = \frac{(t_c - t_a)k}{q_v L_H}; \qquad m = \frac{k}{L_H h}; \qquad X = \frac{a\theta}{L_H^2}$$

For $X < 0.2$, $my_n = X$ or, by introducting the values for X, y, and m:

$$\frac{(t_c - t_a)k}{q_v L_H^2} = \frac{k}{c\gamma}\frac{\theta}{L_H^2} \tag{80a}$$

By rearranging, Equation (80) as written above is found.

From Equation (80) the heating time for a given heat input rate or, conversely, the necessary heat input rate for a desired heating time can be found.

As is apparent from Equation (80), the time necessary to reach a certain center temperature, t_c, is independent of the heat losses. The value, h, does not appear in the equation. The total energy liberation in the piece is determined solely by the volumetric specific heat ($c\gamma$) and the temperature rise of the center above its original value ($t_c - t_a$). For the same total heat input, $q_v\gamma$, however, entirely different heat losses may occur according to the value of h. Hence, according to the value of h, different amounts of heat are available for the heating of the body proper, and consequently a different average temperature will prevail (Fig. 282). Another important conclusion from Equation (80) is that the center temperature rises linearly, in straight proportion to the time (for $X < 0.2$).
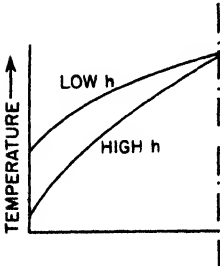
FIG. 282. Final temperature distribution in a slab.

The surface temperatures can be found from Figure 283, in which time functions $\sqrt{X}/m$ are plotted as abscissas and y_s/m as ordinates.

To find the average temperature of the piece, the surface temperatures must be plotted vs. time and the mean surface temperature determined. By multiplying this mean temperature by the boundary conductance, h, the heat loss is found. The difference between the heat input and the heat loss determines the useful heat and therewith the mean temperature.

Example. Long material, insulated on two sides, is heated. Heat loss occurs therefore only toward two sides. The thickness in the direction of the

heat flow is $2L_H = 8$ in.   The properties of the material are: $k = 0.09$ Btu/ft, hr, F; $c_\gamma = 14$ Btu/cu ft, F.   The boundary conductance is: $h = 2$ Btu/sq ft, hr, F.   The initial temperature is 70 F, and the final center temperature desired is 320 F.   The diffusivity of the material is $0.09/14 = 0.00645$ sq ft/hr.   If the
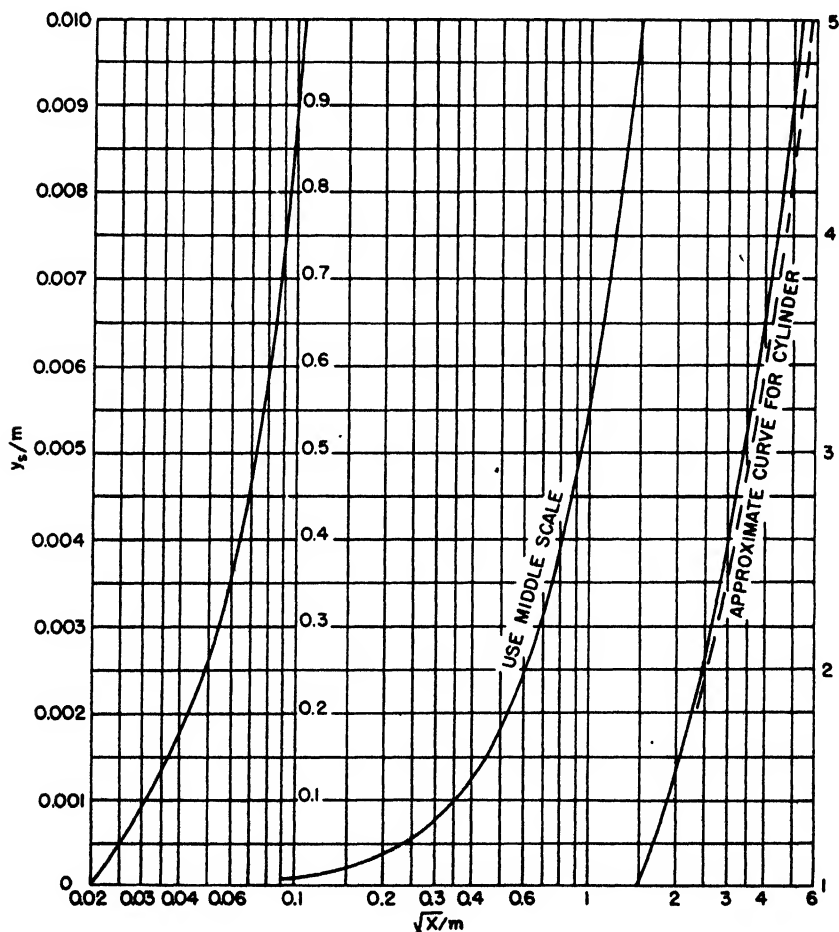
Fig. 283.   Surface temperature function for slabs.[116]

simple relationships given above should be applied, the value $X \gtrless 0.2$.   Hence the maximum heating time to be considered is:

$$\frac{0.2(4/12)^2}{0.00645} = 3.45 \text{ hr}$$

Since a heating time of such length would never be applied in practice, the method of calculation as described is permissible for the given material.

From Equation (80):

$$q_v\theta = 14.250 = 3500 \text{ Btu/cu ft}$$

If q_v' is the rate of heat production per sq ft, hr, then:

$$q_v'\theta = 3500 \times \frac{8}{12} = 2320 \text{ Btu/sq ft} = 0.68 \text{ kwhr/sq ft, hr}$$

Heating in 200 sec calls for a heat generation of:

$$\frac{0.68 \times 3600}{200} = 12.2 \text{ kw/sq ft}$$

in 300 sec, of 8.16 kw/sq ft, etc. From Figure 283, Table XXI is derived, in which the influence of the rate of heat input on the surface temperature may be seen clearly. With 24.4 kw per sq ft the surface reaches 196 F, whereas with 4.07 kw the maximum surface temperature is only 154 F.

TABLE XXI

SURFACE TEMPERATURES FOR VARIOUS INPUT RATES

$\sqrt{X}/m$	y_s/m	Time, sec	Surface temperature, F			
			24.4 kw/sq ft	12.2 kw/sq ft	8.13 kw/sq ft	4.07 kw/sq ft
0.298	0.072	100	196	98.5	64.5	34
0.422	0.132	200	—	180	118	62.5
0.513	0.185	300	—	---	165	92.5
0.596	0.245	400	—	—	—	116
0.666	0.292	500	---	—	—	138
0.721	0.325	600	—	--	—	154

The heat loss from the surface is found by multiplying the mean surface temperature by the boundary conductance ($h = 2$) and by the time of heating. The heat loss subtracted from the heat input (2320 Btu/sq ft) gives the useful heat; finally the useful heat divided by the volumetric specific heat yields the mean temperature of the piece at the end of heating. Table XXII contains the heat loss from the surface (column 2) and the mean temperature (column 3) for different rates of energy liberation (column 1).

Schematically, the final temperature distribution in the piece with different input rates (a, smallest; d, largest) is shown in Figure 284. The following conclusions may be drawn (they hold of course for $X < 0.2$):

(1) The heat loss from the surface is small. Even with the smallest input and longest heating time the loss is only slightly larger than 5%.

(2) The mean temperature is but slightly influenced by the rate of heat generation.

TABLE XXII

HEAT LOSS AND MEAN TEMPERATURE FOR VARIOUS RATES OF ENERGY LIBERATION

Rate of energy liberation, kw/sq ft	Heat loss, Btu/sq ft	Mean temperature of piece, F
24.4	5.45	248
12.2	21	247
8.13	42.8	243
4.07	125	236
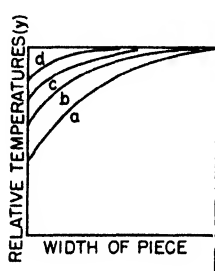
FIG. 284. Final temperature distribution for prolonged (a) and very short (d) heating times. Total heat generation is equal for all curves.

(3) Thus the temperature drop near the surface must be very steep.

(4) With unchanged rate of heat generation per unit volume (note that in the tables the values per unit surface are shown) and with unchanged boundary conductance, the surface temperatures and heat loss do not change for different thicknesses. Their relative importance increases considerably. For example if the thickness of the piece were reduced from 8 to 4 in., then the useful heat with 6.13 kw per cu ft (4.07 kw per sq ft in the example) would reduce from 94.5 to 89.3% of the total input. The mean temperature would decrease from 236 to 222 F. Short heating times are therefore of particular importance for thin pieces.

(5) If a better conducting material is heated, the heat loss from the surface would make itself felt to a greater depth.

For longer heating periods, where $X > 0.2$, the approximation represented in Equation (80) is no longer sufficient. For long dimensionless times, X, it is convenient to refer to the charts available for heating by exposure to a constant temperature source. (See Figures 8–10, pages 12–14), and various references in the literature.[117]) The temperature function, y_H, can be found from the function, y, for a constant tempera-

[117] W. H. McAdams, *Heat Transmission*, McGraw-Hill, New York, 1942. A. Schack, *Industrial Heat Transfer*, Wiley, 1933. H. P. Gurney and J. Lurie, *Ind. Eng. Chem.*, **15**, 1170 (1923). H. Bachmann, *Tafeln über die Abkühlungsvorgänge einfacher Koerper*, Springer, Berlin, 1938. M. P. Heisler, *Trans. Am. Soc. Mech. Engrs.*, **69**, 227 (1947).

ture source by applying a correction factor, w:

$$my_{H_c} = \frac{1 + 2m}{2} - \frac{y}{w^2} \tag{81}$$

The factor w is different for slabs (w_S) and for cylinders (w_C) and may be found from Figure 285.
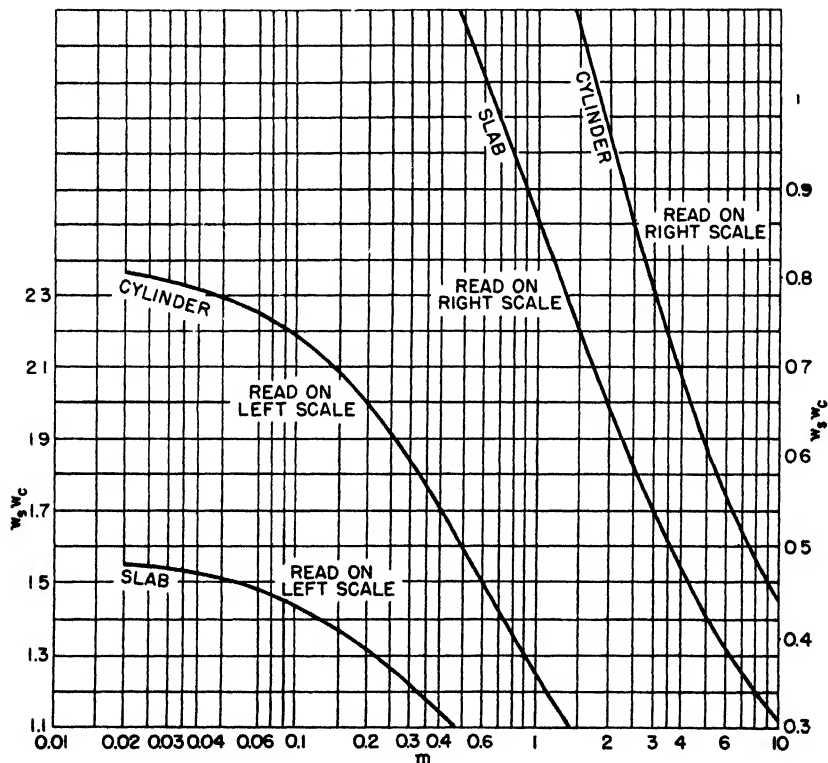
Fig. 285. Temperature correction factors.[116]

CYLINDER

The relationship between heat generation, heating time, and center temperature as expressed by Equation (80) holds also for cylinders.

The surface temperature may be calculated from Figure 283, which, however, is only approximately true for cylinders. For all conditions, when $X < 0.2$ and $\sqrt{X}/m < 1.5$, the error in using Figure 283 is less than 1%. If $\sqrt{X}/m > 1.5$ (but $X < 0.2$) the error may become as large as 8%. For X values > 0.2, the curve developed for constant heat of the surrounding should be used. (For correction factor, see Figure 285.) The transformation is similar to that shown by Equation (80).

(d) Required Development

All previous developments are valid if three basic assumptions hold: one-dimensional heat flow, electrodes or insulation with no mass effect, and thermal and electric properties independent of temperature. Future analytical development should eliminate the necessity for these sweeping assumptions. Almost always heat flow will be in two or more directions: the ends are never completely insulated. Any insulation which may be applied is not without mass, nor are the electrodes, and consequently a heat storage effect will be noticeable. Finally, dielectric constant, power factor, thermal conductivity, and specific heat change with temperature. Therefore the deduction made will not be strictly applicable.

3. Economic Considerations

Since HFC heating is quite young, no exhaustive data on the economic aspects are published. In general, the electric efficiency of the tube generator is 50%, and therefore any saving in heat losses is important—the losses are much more pronounced on the input side. The heat losses increase rapidly with temperature. Therefore efficiencies are better at lower temperatures, and there is a definite limitation as to the maximum obtainable temperature. The limit can be surpassed only by applying combined heating, that is, by overcoming the heat losses by other means of heating.

Tube life expectancy is in the order of magnitude of from 3,000 to 5,000 hr, and a rough indication of tube cost is a value of $40 to $50 per kw output, or $0.011 per kwhr of operation. Little maintenance is necessary besides tube replacements. Main items of operating cost are tube replacements, power cost, and depreciation. The following figures may help in estimating depreciation: the first cost in dollars per kw output decreases with size of the equipment. Taylor [113] indicates as average values $950 per kw for 10-kw output, $700 per kw for 60-kw output, and $480 per kw for 150-kw output. Time for complete depreciation is usually estimated to be from 25,000 to 30,000 hr.

In many instances water-cooled tubes are used, and water requirements may run from 2 to 10 gals per min depending on size of the tubes.

HFC heating will rarely find a justified application based on thermal efficiency. The reason for its increasing usefulness is the uniform and rapid heating it produces. Reduction of the heating cycle, fewer rejections, and increased output must offset the expense of the equipment and the relatively high heating cost.

Selection of Furnaces

1. Electric- or Fuel-Heat Recovery

In Volume I (pages 13–18) the basis of comparison between electric and fuel-fired furnaces was explained. For most furnaces treated in this volume one more factor should still be considered: heat recovery. Compared with other means of heating, the electric furnace is sometimes uneconomical because of the higher cost of energy. This is frequently the greatest single expense item for the electric furnace. Any possible means of reducing power costs will therefore enhance the potentialities for the electric furnace. Although in many cases the insulation of furnaces could be improved, the possible gain in efficiency is relatively small. (Exceptions are such furnaces as salt baths; induction furnaces and high-frequency capacitance heating suffer from a very low electric efficiency). The most promising means of cutting down heat costs is in the use of heat recovery, that is, the use of the heat content of a finished charge for preheating of a new charge. Since preheating is as yet relatively little used, a consideration of its possibilities may not be amiss.

First, heat recovery can be applied also to fuel-fired units. But if the heat costs of both electric and fuel units are reduced an equal amount, the other cost items, which often (although not always) are in favor of the electric furnace, become more important. Heat recovery as used here refers to reclaiming part of the heat content of the charge, not to means of increasing combustion in fuel furnaces, by recuperating part of the sensible heat in the waste gases. In electric furnaces usually no waste gases obtain.

Second, heat recovery is not possible wherever rapid cooling (quenching) is necessary, and it is hardly practical in partial heating (surface heating alone; heating of only one part of the body). Moreover, heat recuperation obviously cannot be applied where the material coming from the furnace is handled hot, as in forging furnaces, furnaces for preheating for presses, etc.

Heat recovery, then, is limited to processes in which slow cooling of the charge is either necessary or at least permissible. Heat exchange

between the cooling charge and a new preheating charge can take place either by radiation or by convection. Transfer by direct contact (conduction) is almost never possible. Heat exchange by radiation usually results in nonuniform cooling and heating. In Figure 286, the cooling
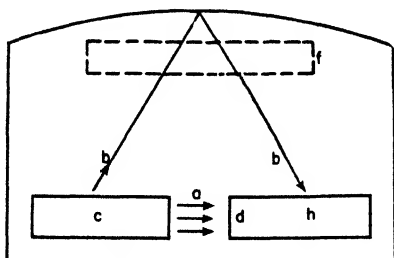
FIG. 286. Heat recuperation
by radiation.
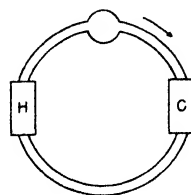
FIG. 287. Heat recupe-
ration by convection.

charge, c, will exchange much heat with the preheating charge, h, through direct radiation (arrows a) and only little through indirect radiation (arrows b). Hence parts d will heat and cool at a rate different from other parts of the charge. Even a fan or blower, f, does not help much.

The most effective scheme of recovery, combining high uniformity and good heat transfer, is to separate the cooling (C) and the heating (H) charge entirely and to effect the heat transfer by convection only. In batch type furnaces (Fig. 287) two separate units are used. Here a
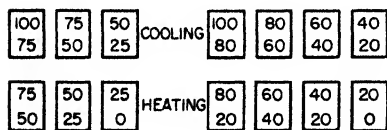
FIG. 288. Temperature gain in
multiple-step heat exchange.
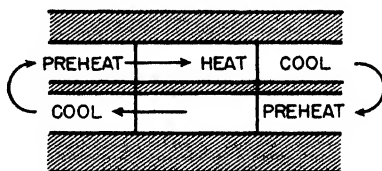
FIG. 289. Heat recuperation
in counterflow.

maximum of 50% of the heat content can be regained. To recover more than 50%, several stations must be installed, and so arranged that the cooling charge, having lost approximately 50% of its heat content to a later charge, is then brought into heat exchange with the next, where it may again lose at best one-half of its present heat content or one-quarter of its original heat. In Figure 288 one scheme including three steps and one including four steps is shown. The method gives, finally, continuous heat exchange, as it may be applied to loads in batch type furnaces or in continuous furnaces. For the latter, two methods are applicable. In the continuous furnace, two streams of charge run in opposite

directions and exchange heat through the air being blown across a separation wall (Fig. 289); or air may be used to cool the charge in the cooling zone (Fig. 290); then the air is transported to the preheat zone where its heat is delivered.
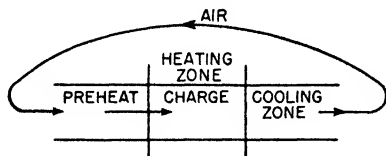
FIG. 290. Heat recuperation by means of air flow.

In considering the economic value and extent of heat recovery, one should remember that the further the heat exchange is carried the greater the first cost of the equipment, and the more material will be tied up in the heating department.

2. Factors Influencing Selection of Electric Furnace Type

Selection of the type of furnace for a given heating job presents a very intricate problem. The same job can usually be done by several methods and in furnaces of different types; however, a complete analysis usually proves one type to be the best fitted for the given purpose. Such an analysis is rendered extremely difficult by the way furnaces are advertised. The description, not only in catalogues but also in articles in the technical press, includes general phrases such as "The material is then heated uniformly to a temperature of — F" or "The power consumption is only — kwhr per lb." In the first example the statement is meaningless without reference to the method of loading and the degree of uniformity obtained (it is explained on page 3 that complete uniformity cannot be achieved, and that each heating process represents a compromise between the requirements for complete uniformity and for output). The statement regarding power consumption is meaningless without reference to a definite degree of uniformity; the latter determines the necessary heating time and, therewith, the heat losses.

Basically, only four factors influence the selection of a furnace type for any given purpose: uniformity of product, output, first cost, and operating cost. *Uniformity of product* has been treated extensively (pages 3–29). The meanings of *output* and of *first cost* are self-evident, but it should be remembered that in partial heating the indication of tonnage has no meaning. *Operating cost* includes power cost, loss of material by scale, labor, cost of rejections, cost of other operations if influenced by the heating process (e. g., reduction in cost of cleaning, of inspection), cost of auxiliary materials (e. g., salt, gas, boxes in pack-case hardening), cost

of maintenance, and such items as cannot be measured in money (comfort of the operator, appearance, etc.).   Most of these factors are not a fixed property of a given furnace design, but apply to a furnace if used for a specific purpose and operated in a specific way.   Reference is made to pages 16 to 18 and 64 to 70 of Volume I.

The four factors are obviously closely interrelated and cannot be treated independently.   Some of the viewpoints offered here may be detrimental to individual commercial interests and will therefore be opposed by manufacturers of the types of equipment condemned.

3. Selection of Electric Furnaces for Metallic Objects

(a) Localized Heating

Two problems come under this general heading: heating the surface only, and heating only part of the length.

SURFACE HEATING

For this purpose it is essential to transfer heat to the surface as rapidly as possible.   This is important not only from the viewpoint of output but also for prevention of heat flow to the center.   Technically speaking, a high boundary conductance (*h* value, page 22) is required. Since the most rapid heat transfer to the surface occurs in induction heating, this method should always be considered as first choice for surface heating.   The low efficiency is not a serious factor because in surface heating the mass to be heated is extremely small.   (Occasional reference to tonnage in describing surface heating is of course misleading if based on the weight of the entire piece.)   Conduction type furnaces (salt or lead baths) offer a second possibility.   However, it is much more difficult to limit heating by this method to very thin layers than in induction heating.   Infrared radiation is very satisfactory for surface heating to low temperatures.

PARTIAL HEATING

Heating of only one end of a piece can be effected either in induction heating or in lead or salt baths.   Which of the two is preferable in an individual problem depends on the pieces to be heated.   Thin or hollow pieces can be conveniently heated by induction.   Heavy sections (*e. g.*, bars, particularly if of magnetic material) are preferably heated in conduction type furnaces.

(b) Through Heating

If material is to be heated through, more or less uniformly, best results are obtained by individual exposure, that is, by exposing each piece to the heat source without heat having to travel from one piece of the

charge, through an air space or contact resistance, to another piece.   This method calls for different furnace types for charges of different natures.

LARGE PIECES WHICH BECAUSE OF WEIGHT AND/OR SHAPE DO NOT LEND
THEMSELVES TO PILING ONE ON TOP THE OTHER

An example is shown in Figure 291 below.

FIG. 291.   Casting of complicated shape.

Heat Transfer.   Radiation or convection type furnaces are usually preferable.   In lead and salt baths (conduction type furnaces) heat is transferred with high and almost equal speed to all parts of the charge; if the mass behind the surface is not uniform (*e. g.*, intricate castings with different cross sections), the uniform and high rate of heat transfer would lead to considerable stresses, because thin parts would be heated through long before the center of the heavy parts reach high temperatures.   Since in conduction type furnaces the rate of heat flow to the surface cannot be controlled, salt and lead baths are not recommended for this purpose. Induction heating would permit control of heat flow, but in the slow heating which is desirable for such pieces the low efficiency of induction heating would become obvious.   Hence induction heating is also unadvisable.

In radiation furnaces it is theoretically possible, although rarely practical, to expose different parts of the body to different temperatures.   In convection furnaces the temperature drop of the air is conditioned by the

location of the piece in the furnace; one light section of the piece cannot be exposed to low air temperatures and another heavier section to high temperatures if the two sections are in close proximity. But both radiation and convection heating easily permit a change of rate of heating with time; if heating takes place sufficiently slowly, temperature differences in the piece can be held at any desired low value.

The selection of radiation or of convection heating for such large pieces, then, depends on the following: at low temperatures the heat transfer by convection is preferable; at high temperatures, that by radiation. In convection heating the heated air can more readily cover intricate shapes having perhaps recesses which in radiation heating cause heat shades difficult to overcome. If the shape of the charge makes extremely slow heating desirable, convection heating offers no advantage from the viewpoint of rate of heat transfer, but may give more uniform coverage of the surface at low as well as at high temperatures. If more rapid heating is permissible, convection heating is recommended for temperatures up to 1000 or 1200 F and radiation heating for higher temperatures.

Handling. Because of the relatively slow heating usually required for such large pieces, continuous furnaces are advisable only for very large output of exactly the same shape and size. Otherwise individual treatment is preferable although it frequently results in a higher power consumption. (The furnace often must cool down before reloading.) For individual treatment main emphasis is to be put on the possibility of accurate loading. Car bottom furnaces, elevator type furnaces, and pit furnaces are suitable. The two latter probably allow more readily achievement of uniform temperatures, and the two former, easier loading. The pit furnace takes longer to cool but has smallest steady-state heat losses and is least expensive in first cost. The elevator type is the most expensive.

Table XXIII summarizes the question of through heating of large and heavy individual pieces.

LARGE PIECES WHICH MAY BE PILED ONE ON TOP THE OTHER

Heavy steel plates and locomotive tires are examples of pieces for this type of loading. Furnaces should be selected with uniform heating in mind. Uniform heating can be approached only if the heat flow across air spaces between individual pieces is avoided (see page 25). As long as this rule is observed no general criteria or preference can be given to any one furnace type.

SMALL PIECES

Very small pieces, such as needles, can be heated only individually or almost individually in a radiation or convection furnace. Lead or salt

TABLE XXIII

THROUGH HEATING OF LARGE AND HEAVY INDIVIDUAL PIECES

I. HEAT TRANSFER

Description of charge	Radiation	Convection	Conduction salt or lead baths	Induction	Capacitance
Uneven cross section, calling for slow heating	No preference from the viewpoint of rate of heat transfer, because slow heating is required in any event	Depending on shape, may give more complete coverage of parts with recesses	Not recommended because thin and thick sections receive equal amount of heat and thicker parts have no time to become uniformly heated	Not recommended because of low efficiency, great weight to be heated, high first cost	If applicable (nonmetallic materials), recommended
Fairly even cross section permitting relatively rapid heating	Preferable for temperatures above 1000 or 1200 F	Preferable for lower temperatures	Not recommended because of high first cost and high power consumption in long soaking process		If applicable, recommended

II. THERMAL EFFICIENCY AND ECONOMIC VIEWPOINTS

Description	Car bottom	Pit type	Elevator type	Continuous furnace
First cost	Medium	Lowest	Highest	For very large uniform output only
Steady-state heat loss*	Highest	Lowest	Medium	
Heat storage in walls*	Medium	Highest	Lowest	
Power consumption for charge: Charge may be withdrawn hot and new charge may be placed in hot furnace*	Highest	Lowest	Medium	
Furnace must cool with or without charge before inserting new one*	Medium	Highest	Lowest	
Ease of loading	Good	Poor	Poor	
Cooling time of furnace	Medium	High	Low	
Achievable uniformity of heat distribution	Low	High	Medium	

* Difference between car bottom and elevator type furnace in respect to this property is slight, and their grading may be reversed. An attempt is being made to estimate the "average furnace" of this type.

baths are not used because of the difficulty of cleaning. For large production, shaker and rotary-hearth furnaces, or possibly conveyor belt furnaces, can be used; for small production, the charge is put on individually exposed pans or even on hot plates.

Somewhat larger pieces, such as nuts, bolts, etc., can be heated in continuous radiation or convection type furnaces (rotary-drum, conveyor belt type) which permit individual exposure. If the desired output is sufficiently large and steady, such continuous furnaces are preferable. They produce material of good uniformity and have low operating cost. Continuous furnaces are particularly advantageous when the material is quenched or undergoes other treatment directly following heating.

For small or irregular production (pieces of different size to be heated in the same furnace within a day), batch type operation is necessary. Baskets or containers permit ease of handling.

For heating piles of small pieces, as in a basket, convection heating or lead or salt baths are desirable, whereas radiation heating should be ruled out. Table XXIV compares the heating of baskets by convection

TABLE XXIV

HEATING OF PILES OF GOODS IN BASKETS OR CONTAINERS

Item	Convection type	Conduction type lead or salt bath
Uniformity		Better
First cost	Lower	
Necessary time of heating		Lower
Power cost	Lower	
Maintenance		
Low temperatures (up to 1000 F)		Lower
Medium and high temperatures	Lower	
Maximum temperature achievable	1700 F	2350 F

and conduction heating. All statements in the table should be considered as general indications, subject to exceptions.

WIRE, STRIP, SHEETS (THIN MATERIAL)

For material of small cross section, individual exposure, as in continuous strand annealing (for strip and wire) or in conveyor furnaces with sheets deposited continuously on the conveying mechanism, is the most advisable method for thermal uniformity. Although continuous strand annealing involves usually more space and higher first cost than treatment in coils or piles, hand-labor cost and energy cost are lower.

Treatment in coils or piles can be conducted in continuous furnaces or in batch type operation. Between the two, relationships exist similar to those between strand heating and coil heating. In Table XXV the arrows point in direction of higher values (e.g., uniformity highest in strand heating and lowest in batch type furnace).

For heating in strands, induction heating and radiation and conduction furnaces can be used. The occasional application of convection furnaces for strand annealing is warranted only for very bright material

TABLE XXV

COMPARISON OF STRAND AND BATCH HEATING

Uniformity	Space requirements	First cost of furnace equipment		Labor cost	Energy cost
↑	↑	↑	Strand heating Coils and piles in continuous furnace Coils and piles in batch type furnace	↓	↓

with low emissivity. Induction heating has not yet been widely applied for this purpose, difficulties arising in strip heating from the problem of uniformity across the width of the strip, and in wire heating from the heat losses from the induction coil, which losses must be offset by the wire. Conduction furnaces are frequently used for certain applications, but less for others, although they would be useful from the viewpoint of atmosphere control. The only limitation in this connection is the problem of surface appearance—spots caused by salt or lead.

Coils can be heated either in radiation or convection furnaces. The main factor in selecting between the two is the question of efficient heat transfer (see page 23). Uniformity is influenced by the method of loading (avoiding heat transfer across the air spaces separating the layers) rather than by the method of heat transfer [118] (radiation or convection, see page 27).

TUBES, RODS

Again, individual exposure is the most desirable solution from the viewpoint of uniformity. Individual exposure is, for example, possible in roller hearth or conveyor belt furnaces. Since such furnaces require comparatively much space, the points discussed above for wire and rod apply also for rods and tubes. For heating in batches see page 163.

4. Selection of Furnaces for Nonmetallic Materials

(a) Rubber, Plastics, etc.

The low diffusivity of nonmetallic materials, resulting in slow and nonuniform heating with any external heat source, makes high-frequency capacitance heating the ideal method for such materials. The main limitation so far are temperatures, because at present such heating equipment usually does not provide for thermal insulation, and the electrodes may offer difficulties at high temperatures. For fairly complicated shapes, ca-

[118] V. Paschkis and J. A. Doyle, *Wire and Wire Products*, **21**, 369 (1946).

pacitance heating encounters difficulties in producing uniform heat generation. If nonmetallic material is in powder or granular form and thus stands tumbling, rotary drum furnaces can be applied, or, if the electrodes can be devised for the necessary temperature, high-frequency capacitance heating. Neither of these two heating methods can be used if solid shapes have to be heated to high temperatures.

(b) Ceramics

Since ceramic materials are usually heated through, the problem of partial heating does not arise. Even if only surface effects are required, as in glosting, slow heating must be applied to avoid cracking from temperature differences. The problem of heating a piece through is complicated by the low thermal diffusivity of nonmetallic materials.

Regularly shaped pieces, such as china tableware, as well as industrial and sanitary objects, are generally arranged in furnaces in orderly stacks. For temperatures up to 1700 F, convection type furnaces would be best. Unfortunately, many processes in the ceramic industry require temperatures beyond the reach of convection furnaces.
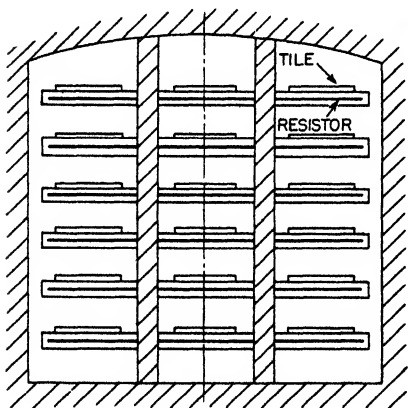
Fig. 293. Batch type furnace for ceramics.

Fig. 292. Individual exposure of tiles in a multiple-channel furnace.

For material which can stand direct exposure to flames (without saggers, etc.), as is true with certain types of refractory bricks, the field belongs to direct-heat fuel-fired furnaces. The material should be stacked loosely so that the combustion gases can travel between the individual objects. However, where contact with flames is not permissible, individual exposure in radiation type furnaces yields best results and the electric furnace, operating without a muffle, has a legitimate field of application.

Figure 292 is an example of individual exposure of tiles in such a furnace. Furnaces of this type have been developed in Europe. Though

in a furnace loaded as shown in Figure 293 the pieces in the center undergo an entirely different heating cycle from those near the outside, such furnaces are in operation.   There is thus a wide field of research open: for ceramists, to determine how far the heating time could be cut in case of individual heating; and for furnace engineers, to develop furnaces for individual heating.   The latter problem may eventually be solved by high-frequency capacitance heating.

5. Review of Types of Heating

The five types of heat generation treated in this text as applied to heating (as distinguished from melting) have distinct features which make each of them preferable for certain jobs.   These features, explained in the sections describing the furnaces and in the preceding paragraphs on selection of furnaces for given tasks, are summarized in Table XXVI. Statements of suitability and of properties that are relative are marked by (r), preferable choices by (p).

TABLE XXVI

FIELDS OF APPLICATION AND PROPERTIES OF VARIOUS METHODS
OF ELECTRIC HEATING

Fields of application	Radiation	Convection	Conduction	Induction	High-frequency capacitance
APPLICATIONS					
Metallic materials	Yes	Yes	Yes	Yes	No
Nonmetallic	Yes	Yes	No	No	Yes
Partial heating (metallic material)	No (r)	No (r)	Yes	Yes	No
Through heating					
metallic material thin	Yes	Yes	Yes (p)	Yes (p)	No
metallic material thick	Yes (p)	Yes (p)	No (r)	No (r)	No
Extended holding times	Yes (p)	Yes (p)	Yes	No	No
PROPERTIES					
Rate of nonproportional losses (see Vol. I, p. 64)	Low	Low	High	High	High
Rate of proportional losses	Practically zero	Practically zero	Low	Very high	Very high
Lends itself to heat recovery	Yes	Yes (p)	No (r)	No	No
Lends itself to automatic handling of charge	Yes	Yes	Yes	Superior	No (r)
Temperature uniformity in through heating	Good	Good	Very good	Low	Very good
Control of process					
by time	Yes (r)	Yes (r)	Yes	Yes	Yes
by temperature	Yes	Yes	Yes	No	No

A P P E N D I X

Dielectric Properties of Various Materials

Material	Power factor	Dielectric constant	Frequency, megacycle
Woodflour phenolics molding material	0.04	3.5	1
Wood (average)[a]	0.035	3.0	1
Neoprene rubber[a]	0.06	12.0	1
Buna N[a]	0.17	9 0	1
Glass[d]	0.002–0.004	4.5–6.2	1
Hard rubber[d]	0.005–0.009	2–3	1
Steatite[d]	0.003	6.1	1
Spruce[b]	0.08		0.1
Spruce[b] [c]	2.5	2.9	10
Oak[b]	1.6		0.1
Oak[b]	2.6		10
Spruce, 2% moisture[c]	5.8	2.4	45
Spruce, 8% moisture[c]	7.8	2.8	45
Spruce, 12% moisture[c]	11	3.2	45

[a] Anonymous, *Elec. World*, **122**, 91 (Oct. 21, 1944).
[b] J. P. Taylor, *Trans. Am Soc. Mech Engrs.*, **64**, 201 (1942).
[c] R. A. Bierwirth and C N. Hoyler, *Proc Inst Radio Engrs.*, **31**, 529 (1943).
[d] F. E. Terman, *Radio Engineers' Handbook*. McGraw-Hill, New York, 1943.

SUBJECT INDEX

Note: Listings in the index refer to appliances as well as to furnaces unless both are mentioned separately (*e.g.*, "Furnace atmosphere" refers to the atmosphere in appliances as well as in furnaces).

For Reference